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THE ECO-PROFILE OF THERMOPLASTIC PROTEIN DERIVED FROM BLOODMEAL

A thesis
submitted in partial fulfilment
of the requirements for the degree
of

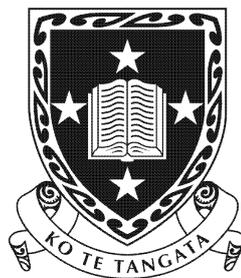
Master of Science in Materials and Process Engineering

at

The University of Waikato

by

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**University
of Waikato**

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o Waikato*

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Abstract

Life cycle assessment (LCA) is a method that can be used to evaluate the eco-profile of a product over a portion of its life cycle. Novatein Thermoplastic Protein (NTP) is a second generation bio-based polymer being developed at the University of Waikato, using bloodmeal as a feedstock. The objective of this study was to estimate the cradle to gate eco-profile of a hypothetical commercial process producing NTP. Specific objectives were to:

- Estimate non-renewable energy use and greenhouse gas emissions.
- Identify which portions of the cradle to gate system have the greatest contribution to such impacts.
- Evaluate this material against other polymers.

It was found that the allocation method used for the multiple outputs of farming and meat processing had a significant influence on the non-renewable primary energy and greenhouse gas emissions attributed to NTP. This resulted in great differences between the eco-profile of NTP relative to other polymers.

The production of bloodmeal was found to have the largest contribution to both non-renewable primary energy use and greenhouse gas emissions of all life cycle phases. This was even more pronounced when impacts from farming and meat processing were allocated to blood or bloodmeal on a mass basis. This is in contrast to fermentation based polymers, which typically have impacts dominated by energy supply for fermentation and recovery, rather than production of biomass. If allocation from farming is based on the mass of blood as proportion of live weight, 13 kgCO_{2e}/kg polymer are attributed to NTP, considerably higher than the 1 – 2 kgCO_{2e}/kg polymer typical of other bio-based plastics (when using conventional energy) and conventional commodity polymers. Non-renewable primary energy in this scenario is 48.28 MJ/kg polymer, similar to that of other bio-based polymers.

If allocation is based on the mass of bloodmeal, excluding wastes and losses, only 28.41 MJ/kg polymer are attributed to NTP. Emissions are still slightly higher

than other bio-based polymers at 2.82 kgCO₂e/kg polymer, but in the same order of magnitude.

Alternatively, blood can be considered a waste with regard to farming and meat processing, and only the impacts of blood drying and associated transport are attributed to bloodmeal. In this case 24.03 MJ non-renewable primary energy and 0.35 kgCO₂e/kg polymer greenhouse gas emissions are attributed to NTP. For comparison, the production of polyethylene uses 72.3 MJ/kg non-renewable primary energy and releases 1.89 kgCO₂e/kg polymer.

It was concluded that the most appropriate allocation scenario is to only attribute the impacts of blood drying (and associated transport) to bloodmeal, and not any impacts from farming and meat processing. Under such as scenario, the production of NTP has the potential to reduce non-renewable primary energy use and greenhouse gas emissions by replacing synthetic polymers or other bio-based polymers. For each potential application, however, a full cradle to grave life cycle system should be considered to ensure that impacts from the use and end of life phases do not outweigh any differences in impacts from manufacture.

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“He did not enter by means of the blood of goats and calves; but he entered the Most Holy Place once for all by his own blood, having obtained eternal redemption. The blood of goats and bulls and the ashes of a heifer sprinkled on those who are ceremonially unclean sanctify them so that they are outwardly clean. How much more, then, will the blood of Christ, who through the eternal Spirit offered himself unblemished to God, cleanse our consciences from acts that lead to death, so that we may serve the living God!” – The book of Hebrews, Chapter 9 vs 11-13.

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1 Introduction

Concerns about the depletion of non-renewable resources and contributions to climate change from fossil fuel use have led to the development of alternatives to common petrochemical polymers. Bio-based polymers seek to overcome environmental problems by the use of renewable biological feedstocks. The growth of crops for polymer feedstocks, however, competes for land with both food production and growing demand for biofuels.

A second generation of bio-based polymers has been proposed, that utilise alternative renewable feedstocks such waste streams or low value by-products of existing activities. Bloodmeal is one such feedstock. It is a renewable source of inedible protein that is produced by existing agriculture and used as a low value fertiliser. Treatment of bloodmeal with particular combinations of additives overcomes interactions between protein chain movements and allows thermoplastic processing at temperatures that do not degrade the protein, producing Novatein Thermoplastic Protein (NTP).

The use of a renewable feedstock does not, however, guarantee that such a polymer is necessarily environmentally friendly. Other bio-based polymers have been shown to require considerable amounts of energy in the processes required to convert renewable biomass into a functionally equivalent replacement for petrochemical polymers. In some cases, energy use even exceeds that required to make the polyethylene or polypropylene. It is therefore important that bio-based polymers be evaluated against alternatives to ensure that any claims of environmental benefits are not simply greenwash, but are genuine reductions in environmental impacts. Life cycle assessment is a technique that can be used to investigate and compare products with regard to environmental impacts.

The objective of this study was to apply LCA methodology to NTP, on a cradle to gate basis, to:

- Estimate non-renewable energy use and greenhouse gas emissions that can be attributed to the production of NTP.
- Identify which parts of the production of NTP have the greatest contribution to these environmental impacts.

- Compare NTP with other bio-based polymers.

This thesis is structured in a fashion partially based on the international standards on life cycle assessment. Chapters Two, Three and Four introduce the concepts involved in a life cycle assessment of bio-based polymers. Chapter Five includes the goal and scope definition, along with inventory analysis and impact assessment. Chapter Six considers life cycle interpretation, including a discussion of the life cycle inventory before drawing conclusions on the comparison with other bio-based polymers.

The main limitation in this study is that it is performed only on a cradle to gate basis and does not include any impacts from use of a product or disposal at the end of its life.

2 Bio-based polymers

2.1 Polymers and their problems

Although thermoplastic polymers are relatively new materials, developed in the twentieth century, they have become so ubiquitous it is hard to imagine modern life without them. From cellphone and computer casings, to car door panels, shopping bags, toys, furniture and more, their unique material properties and ease of manufacture have ingrained polymers as part of the human environment. Unfortunately, discarded polymers are also becoming part of the natural environment. Furthermore, commodity polymers are manufactured from fossil fuels and there are concerns about depletion of these resources.

Polymers are organic macromolecular structures made up of linked repeating units of smaller groups of atoms, called monomers. In general they have useful properties such as a low density, resistance to corrosion, thermal and electrical insulation and ease of manufacture [1]. Numerous factors affect the interactions between macromolecules and thereby the exact material properties of an individual polymer such as stiffness, strength and toughness, useful operating temperature and resistance to wear [1]. These factors include the monomers themselves, the way these monomers are connected, the number of monomers in each macromolecule, and the presence of other chemicals such as plasticizers.

A variety of different monomers can be used to make polymers. Polymers in which all the monomers are the same are called homopolymers. Polymers with more than one type of monomer are called co-polymers. The properties of these are dependent on the proportions of the different building block as and how these are joined [1].

Thermoplastic behaviour is exhibited by linear polymers where the monomers are joined end on end to form long chains but these chains are not covalently bonded to each other. When heated they will melt, and when cooled they will solidify [1]. These long chains are not aligned rigid rods, but are untidily coiled around each other with entanglements and linked by secondary forces. As chain length increases entanglements per chain increase and this can lead to increased strength. It can, however, also increase the viscosity of a polymer melt making processing

more difficult [1]. In any polymer, the size of each individual molecule is not uniform and the length of the chains, or degree of polymerisation, is best described as a distribution of molecular weights.

At low temperatures, thermoplastic materials are in a glassy state. Interactions restrict chain mobility, effectively freezing the chains in place. As temperature is increased, these interactions are overcome and the chains are able to move around each other more readily, which results in rubbery properties. The temperature at which this occurs is called the glass transition, and is different for different polymers. It is influenced by the chemical and steric interactions between side groups of the monomers, the distribution of chain lengths, and the degree of crystallinity in the polymer. As temperature continues to increase this rubbery material's viscosity decreases until it is in a liquid state [2]. It is this reversible transition from glassy to rubbery state and then into a viscous melt at easily attainable temperatures that makes for the ease of polymer processibility.

The properties of thermoplastics allow for particular processing methods such as extrusion, injection moulding, blow moulding and compression moulding. These enable polymers to be manufactured cheaply and easily into all sorts of useful shapes for all sorts of useful applications.

If the monomers are not only joined end on end, but also elsewhere, the result is a network polymer [1]. Depending on the density of the crosslinking, the material properties can vary. Some materials crosslink irreversibly as temperature is increased, so that when cooled down the crosslinking remains. If heated again, these materials will not melt. Such behaviour is called thermosetting. Crosslinking can also be induced by chemical reactions, such as the vulcanization of rubber [1].

By using different monomers, different amounts of crosslinking and different distributions of molecular weights, a large range of different polymers, often mistakenly just called plastics, can be manufactured with a large range of properties suited to a variety of different applications.

2.1.1 Environmental concerns

Despite being very useful, polymers have some downsides; most importantly they require the use of finite resources, lead to accumulation of waste and the production of greenhouse gases [3].

The vast majority of polymers are made from non-renewable feedstocks that have taken millions of years to form [4]. Ease of production and processing, combined with low prices of oil in the latter half of the 20th century contributed to the widespread production of polymers, and the emergence of an extensive oil based polymer industry [3]. Oil is a finite fossil resource, and although estimates vary as to how long reserves will last, fossil fuel reserves are running out [5]. The large scale manufacture of plastics from such resources now is a legitimate current concern, as it hastens the rate with which the peak of world oil production approaches [4].

In addition, the vast quantities of polymers produced each year represent a significant waste management problem. Over 60 billion pounds of polymers are discarded annually into waste streams in the United States alone [4].

Some of the properties that make polymers useful are considered disadvantages concerning disposal [6]. As litter, conventional polymers remain in the environment and can be hazardous to living creatures such birds, fish and other animals [4]. Most of the marine litter worldwide is made up of polymers [7]. Even when collected, rather than being discarded directly into the environment, polymer waste has to be disposed of somehow. As landfills fill up, partly on account of polymers, there are problems finding new sites [4].

Recycling of polymers has limitations and over 90% of polymer waste is still not recycled [4]. Polymer waste is generated in large quantities from agricultural operations such as mulch films, greenhouse components, irrigation tubes and general purpose containers. Recycling of this waste can be difficult due to contamination with soils, foods and chemicals [8].

Incineration is another option for waste disposal, and although heat can be recovered and used, it still does not reduce dependence on non-renewable materials and can there are concerns about the toxicity of pollutants released [4].

Additionally, when petroleum based polymers are burnt at the end of their life, fossil carbon is released into the atmosphere [3]. The release of greenhouse gases from the use of fossil fuels is the largest known human contribution to climate change [9]. The production and transport of these materials also largely rely on the oil industry for fuel, causing further resource depletion and greenhouse gas emissions.

2.2 Biopolymers: offering potential solutions – and some confusion

Environmental concerns have led to the investigation of alternative materials that are functionally equivalent to commodity polymers, but could be produced sustainably.

Biodegradable polymers have been developed to address concerns about waste build-up and polymers derived from renewable biological feedstocks have been developed to address concerns about depletion of fossil resources. Historically, both have sometimes been referred to as “bioplastics” leading to some ambiguity. Whilst there is some overlap, not all biodegradable polymers are made from biomass, nor are all polymers made from biological resources necessarily biodegradable. Additionally, not all polymers are thermoplastics.

A recent report published by the biopolymer industry organisation in Europe, specifically addressed plastics from biological sources, and advocated the use of “bio-based plastics” over the word “bioplastics” to avoid this ambiguity. Additionally it provides a definition for bio-based plastics as “man made or man processed organic macromolecules derived from biological resources and for plastic and fibre applications (without paper and board)”[10].

This thesis is primarily concerned with thermoplastic polymers that are both bio-based and anticipated to be biodegradable. Figure 1 shows a variety of polymers that can be manufactured from renewable resources and which are regarded as biodegradable, along with commercial manufacturers of these.

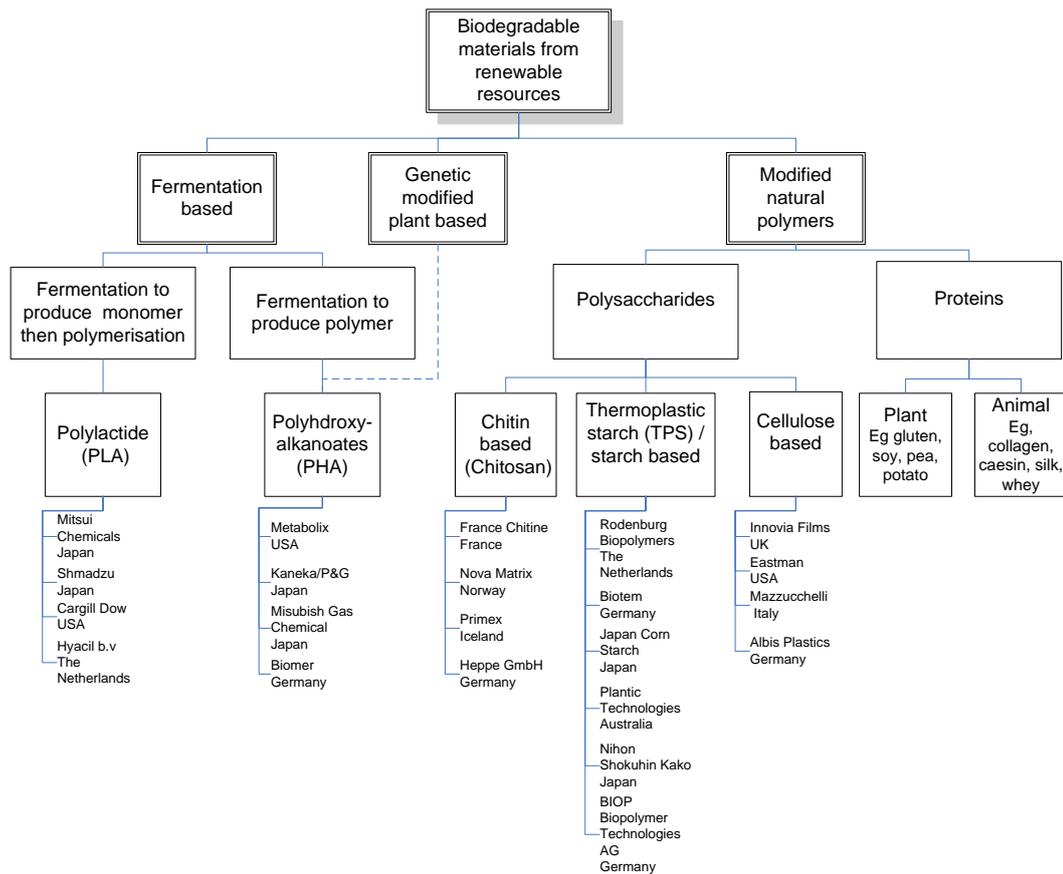


Figure 1: Biodegradable polymers produced from renewable resources adapted from [11]¹.

2.2.1 Biodegradable polymers

Biodegradable polymers were developed in response to the limited capacity of landfills becoming a threat and a bad public image of polymers as being unenvironmentally friendly. Advances in recycling, and the implementation of waste to energy incineration facilities have reduced the impetus for biodegradable polymers [12, 13]. Biodegradable polymers are not useful for all applications. In some cases, it is their durability and resistance to weathering, wear and degradation that make polymers such useful materials. However, where recycling may be inhibited by cost or technical difficulties, biodegradability can be an advantageous property [8].

¹ PHAs are normally produced by bacteria in fermentation processes but can also be synthesized by genetically modified plants.

Although widely used, the term “biodegradable” like “bioplastic” can be ambiguous. Commercial bulk polymers are organic molecules. In time, they may degrade and this organic carbon is mineralised to CO₂, but, it is the time scale that is important with these molecules taking longer to degrade in the environment than is within the human capacity to notice [14]. To market a product as biodegradable it is important to state where and how it will degrade and in what time frame. Readily biodegradable materials allow new waste management options not available to conventional polymers, such as composting. Standards on compostability require a material not only to be biodegradable, but to have a set of properties including biodegradability, but also disintegratability, no heavy metals or ecotoxicological compounds and no negative effects on the composting facility [14].

2.2.2 Bio-based polymers

Bio-based polymers address reliance on non-renewable energy use can be produced from biomass in one of three principal ways [11]:

- 1) Modification of natural polymers.
- 2) Fermentation to produce bio-based monomers which can then be polymerised.
- 3) Production directly in microorganisms (via fermentation) or in crops that have been genetically modified.

2.3 Types of bio-based polymers

2.3.1 Modified natural product polymers

Whilst polymeric materials only emerged on an industrial scale in the twentieth century, nature has been making use of polymeric structures since life began. The building blocks of life are made from long chains of repeating units of sugars or amino acids. DNA, proteins and carbohydrates such as starch, cellulose and chitin are all macromolecules that have polymeric structures. Some of these biomolecules can be collected in bulk and processed to behave as polymer materials. In fact, the first thermoplastics to be developed throughout the second half of the 19th and early 20th century were based on modification of natural

polymers. It was only as oil industry grew that synthetic polymers largely replaced bio-based materials [3].

2.3.1.1 Polysaccharides

Polysaccharides are polymers of carbohydrates such as glucose. They play important biological roles with regard to energy storage and structural integrity [15].

Starch is a mixture of linear and highly branched polymers of glucose called amylose and amylopectin respectively. It is one of the main energy storage molecules in a number of plant species and therefore abundant in nature. It can be extracted from a number of different crops, but depending on crop, it has a different distribution of the linear and branched forms as well as different degrees of polymerisation [11]. Dry native starch cannot be processed by thermoplastic melt processing as it thermally degrades before passing through a glass transition. Plasticizers can cleave hydrogen bonds between starch molecules, changing semi-crystalline starch granules into a homogenous material that can be processed below its decomposition temperature [11]. Both pure starch polymers and starch/petrochemical blends are commercially available [12].

Structural polysaccharides such as cellulose and chitin have very different properties from those used for storage, despite similar compositions [15]. Cellulose based plastic materials were among the first to be developed in the second half of the 19th century [3]. Cellulose is the most abundant organic material on earth, and is a major structural component in cell walls of plants [11]. Like native starch, cellulose decomposes before undergoing melt flow so it is chemically converted to cellulose esters before processing [11].

Chitin has a similar structure and function to cellulose, but with a hydroxyl group replaced by an amino group at a specific carbon in the monomers. Unlike cellulose which only occurs with a parallel arrangement of chains running in the same direction, chitin occurs in forms with parallel chains, with anti parallel chains, or with both. It is found in the exoskeleton of insects, spiders and crustaceans [15]. Wastes from the seafood processing industry containing chitin are converted to a material called chitosan by a deacetylation process [11].

2.3.1.2 Proteins

Proteins are naturally occurring polymers made up of sequences of covalently bonded amino acids. They are manufactured within cells through DNA transcription and translation. Proteins perform numerous functions essential to life, including catalysis (as enzymes), transport of small molecules, regulation of gene expression and structural functions [15].

There are 20 commonly occurring amino acids with a basic structure shown in Figure 2. Different groups in the “R” result in a variety of chemical properties.

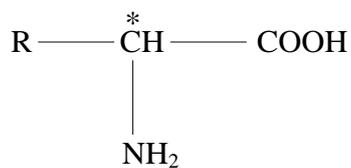


Figure 2: Generic Structure of an amino acid. The asterisk represents an asymmetric carbon [16].

The amino acid’s side chain (R group) can either be polar, non-polar, acidic or basic [15]. Covalent linkages (called peptide bonds) form between the NH_3 and COOH groups with the condensation of water. The properties of the amino acid side chains influence the 3-dimensional structure of proteins [16]. In enzymes these groups are also important in determining the properties of the “active site” responsible for catalysis of biochemical reactions. For example, acidic groups can act as a nucleophile, or basic groups can act as proton receivers and acceptors [15].

Protein structure is defined at four levels: The primary structure is the sequence of amino acids. The secondary structure is where chain sections form regular structures such as coils (called alpha-helices) or pleated sheets (known as beta-sheets). The tertiary structure is the way that the chains fold and bend into more complex three dimensional shapes. In proteins that are made up of more than one sequence of amino acids, the quaternary structure is the way multiple chains interact to form larger structures. When the secondary, tertiary or quaternary structures are disrupted, the protein is said to be denatured. When the primary structure is broken, the protein is said to have been degraded. Apart from the primary structure which is determined by covalent linkages, the other levels of structure are mainly influenced by non-covalent forces [15].

To process proteins thermoplastically, these non-covalent interactions need to be overcome without damage to the covalent linkages in the amino acid chain. This requires a way to overcome the thermodynamic barriers of chain unfolding, without heating to a temperature where the chains undergo thermal decomposition. As with starch, addition of selected chemicals can be added to plasticize proteins. Small molecules can bind preferentially to the portions of the polypeptide chain that interact with other chains, disrupting the intermolecular interactions. This can increase chain mobility and reduce the glass transition to temperatures lower than those where the polypeptide backbone degrades [17].

Thermoplastic materials derived from proteins are yet to be commercialised on a large scale [11].

2.3.2 Fermentation followed by polymerisation- PLA

An alternative to the extraction and modification of natural polymers is the use of biological processes to produce a monomer that can then be polymerised. Biomass can be turned into a polymer via fermentation to produce a suitable monomer, such as lactic acid, followed by polymerisation.

Poly(lactide) (PLA) is a thermoplastic polymer with crystalline structure and properties suitable for processing by injection moulding, film forming, blown-film, spinning, blow-moulding, extrusion and expansion moulding [18]. It is used in packaging, paper coating, fibres, films and various moulded articles [11].

Although many different feedstocks could be fermented to produce lactic acid, corn sugars are used commercially [19]. A summary of the process used by Cargill Dow is shown in Figure 3. Different manufacturers may use different processes to polymerise the lactic acid. For example, Cargill Dow use a solvent free polymerisation process whereas Mitsui Chemicals use a solvent based one [11].

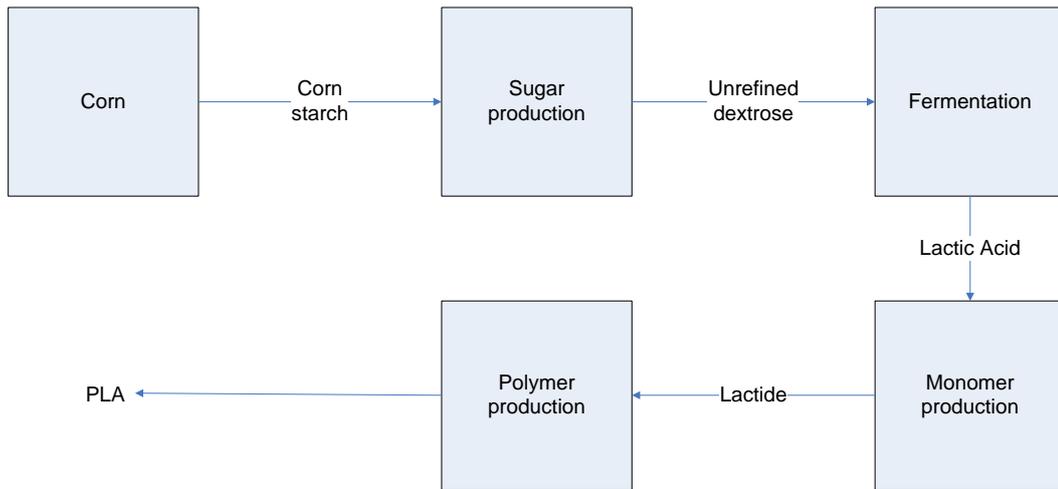


Figure 3: PLA Manufacturing Overview, reproduced from [19].

2.3.3 Fermentation to directly produce a polymer-PHA

Polyhydroxyalkanoates (PHAs) are a class of bio-derived aliphatic polyesters which can be manufactured intra-cellularly [20]. A source of biomass is obtained (typically from crops) and then converted into intracellular PHA via microbial fermentation. The polymer is extracted and purified with yields of up to 90% of dry cell mass [21]. An example production and recovery process is shown in Figure 4.

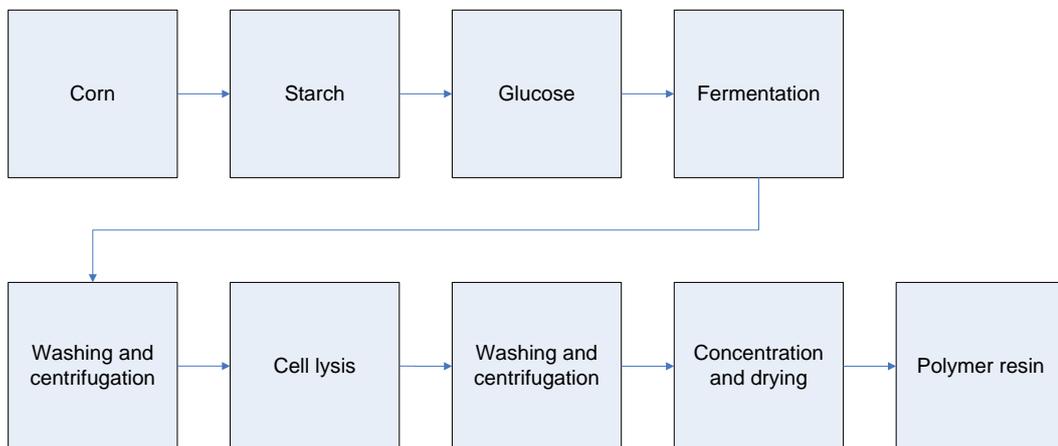


Figure 4 A PHA fermentation and recovery process. Adapted from [16].

Depending on the organisms and growth mediums used, a variety of structures can be formed each with unique properties [22]. Various kinds of crops can be used, including corn, soy beans and sugarcane [23-25]. In addition some research has been done utilising fermentation of waste streams such as industrial wastewater [26]. The most commonly produced and studied variant is

polyhydroxybutyrate (PHB) which has similar properties to many industrial polyolefins [20, 27]. In addition to production by microbes in fermentation processes using plant feedstock, polyhydroxyalkanoates can be produced directly in the cells of transgenic plants [28].

2.3.4 Bio-based conventional polymers that do not biodegrade

Ethylene is an important precursor to many different products, including commodity polymers such as polyethylene and PVC. It is normally produced by steam cracking of fossil fuels, but can also be produced by the catalytic dehydration of ethanol, which can be produced from biomass via fermentation [29]. This allows conventional polymers like polyethylene to be produced from renewable feedstock. This does not impart other “green properties”, such as biodegradability and compostability, but has the advantage of equivalent properties and performance as fossil based polymers [30]. Such material, then, addresses the concerns of resource depletion, but not waste buildup in the environment.

2.4 Food supply and the drivers for second generation bio-based polymers

If production of bio-based polymers from food crops is ever to approach the level of fossil based polymers there will be serious competition with food production [31]. Furthermore, many of the same raw materials that are used for bio-based polymers are also already used for the production of biofuels such as ethanol [18].

Production of biofuel only makes up a small proportion of the total world demand for crops but makes up a large proportion of the increase in demand. A 2008 report to the New Zealand Energy Efficiency and Conservation Agency and Ministry of Agriculture and Fisheries Policy found that biofuels accounted for only 5% of the total demand for grain, but 60% of the increase in demand from 2005 – 2007. Likewise biofuels production uses less than 10% of the total demand for vegetable oil but contributed to more than half of the increase in demand for vegetable oil from 2005 – 2007 [32].

As world population continues to grow on a finite planet, there will continue to be conflicting demands on resources. This could be mitigated by a second generation

of bio-based polymers which use renewable sources that do not compete with food supply. Such sources include biological wastes and crops grown on marginal land [31].

2.5 Novatein Thermoplastic Protein

Blood from slaughtering animals must be treated rather than discharged into the environment, otherwise its very high biological oxygen demand causes a pollution problem [33]. Blood can be separated to produce plasma and other fractions that can be used in food, but in practice a large proportion is not able to be collected hygienically so it is used to produce bloodmeal instead [34].

The dry matter of blood is 90 – 95% protein [33]. This high protein content, coupled with the fact that bloodmeal is a by-product of existing agricultural activity, mean bloodmeal is a great candidate for conversion to a second generation bio-based polymer that does not compete for land use with crop production.

Research at the University of Waikato has shown that bloodmeal can be converted to a thermoplastic material. By processing with a combination of protein denaturants, reducing agents and plasticizers, bloodmeal can be extruded and injection moulded. This means it can be shaped for a number of applications. Varying the exact mix of additives varies material properties, but processing with 3 parts per hundred bloodmeal (pph_{bm}) sodium sulfite, 60 pph_{bm} water, 3 pph_{bm} sodium dodecyl sulphate and 20 pph_{bm} urea has been shown to produce a ductile polymer after conditioning, which has similar tensile strength and Young's modulus to low density polyethylene [17].

It is anticipated that Novatein Thermoplastic Protein (NTP), being predominantly protein, will be biodegradable and meet standards on compostability. Conclusive composting trials are yet to be completed.

Novatein Limited has been established to develop, produce and market the material on behalf of the University of Waikato.

As environmental considerations are an important motivation for the development of bio-based and biodegradable polymers, their environmental performance needs

to be compared with the petrochemical polymers they could replace [12]. For this reason the environmental impacts of Novatein Thermoplastic Protein should be investigated. One method of investigating such impacts is life cycle assessment and this method is described in the next chapter.

2.6 Conclusions

Both bio-based and biodegradable polymers have been proposed as solutions to some of the problems posed by petrochemical based polymers. Bio-based polymers use renewable resources as a feedstock in their manufacture, and address concern regarding depletion of non-renewable resources such as fossil fuels in polymers manufacture, and can be made in a variety of ways.

Biodegradable polymers, on the other hand address, concern about disposal of polymers at the end of their useful life. There are a variety of polymers that address both these concerns, i.e. being both bio-based and biodegradable. These materials are manufactured from biological feedstock in multiple different ways.

With bio-based polymers made from crop sources, competition with food supply and crops for biofuels is of concern and a new generation of bio-based polymers that use alternative feedstocks would be advantageous. One such material is Novatein Thermoplastic Protein, which uses bloodmeal, a renewable agricultural by-product as a feedstock. Being protein based, it is expected that it will be biodegradable, and hence avoid build-up of waste in the environment.

3 Life cycle assessment

3.1 Introduction

Life cycle assessment (also called cradle to grave analysis) is a tool used for assessing the environmental impacts of a product throughout its whole life cycle. This begins with extraction of raw materials from the earth, subsequent manufacture of the product using these materials, usage for its intended function, and disposal once its useful life has ended.

The concept was developed during the last few decades of the twentieth century and a number of different names were given to studies attempting to look at the effects of manufacture, use and disposal of a product in a holistic way [35]. The methodology was standardised as life cycle assessment in 1997 with the introduction of ISO 14040 by the International Standards Organisation, which specifies the framework, procedures and limitations of such a study [35, 36]. Additional standards describe the activities within life cycle assessment in more detail. These were ISO 14041, 14042 and 14043 but these have been superseded internationally by ISO 14044 so that only two standards are required to conduct life cycle assessment. The new standards have been updated for readability, but the requirements and technical content have not been affected except for errors and inconsistencies [37].

ISO 14044 is not yet available from Standards New Zealand [38]. The older standards are still current for New Zealand and have been used in this thesis.

A life cycle assessment in accordance with ISO 14040 includes the following activities [36];

- 1) Goal and scope definition [39].
- 2) Life cycle inventory analysis [39].
- 3) Life cycle impact assessment [40].
- 4) Life cycle interpretation [41].

The entire process is performed in an iterative manner; as data is collected during inventory analysis and impact assessments are interpreted, refinements are made in the goal and scope which flow through to improvements in the later steps.

There are several purposes that a life cycle assessment may be used for [42]. The most basic is to create an environmental profile for a particular product. This, however, is a limited use of the tool. The purpose of creating an environmental profile of a product is ultimately to compare it to alternatives. It follows that the main purpose of life cycle assessment is to compare alternative products or materials for a particular function, or to compare alternative processes with regard to their impact on the environment. Ultimately, such information is used to aid decision making.

A further use of life cycle assessment is to improve processes with regard to their impact on the environment. In conducting an assessment, the life cycle is broken down into unit processes which are each evaluated for their contribution to effects on the environment. This enables the portions of the life cycle which have the most significant contribution to environmental impacts, or “hot spots,” to be identified. Efforts to improve the overall life cycle can then targeted to these portions [35, 42].

3.1.1 Advantages of life cycle assessment

Life cycle assessment is a formal procedure for creating an environmental profile. The advantages of LCA are that it is an internationally standardised procedure with flexibility for particular project goals. It can consider multiple kinds of environmental impact, such as climate change, acidification, energy use, resource use, eutrophication and environmental toxicity, and provides practical applications of the profiles created.

The concept of life cycle analysis developed out of an understanding that to accurately assess environmental impacts of a product, it is not enough to look at its manufacture, usage or disposal alone, but of the combined impacts of all these steps. At each stage in a product or material’s life there are material and energy inputs and outputs, resources used, as well as waste and emissions, all contributing to the product’s total performance in environmental terms.

Life cycle assessment normally addresses multiple impact categories, although some studies with specific goals may only look at a few in detail. When using life cycle assessment in decision making, it is important to consider which impacts are relevant and most significant, and ensure they are included.

3.1.2 Considerations when applying life cycle assessment

As with any analysis, care must be taken to apply life cycle assessment appropriately for a particular situation.

Life cycle assessment only considers environmental aspects and does not consider economics or social concerns. In terms of the triple bottom line of sustainability (people, planet and profit) it only looks at one of these three areas. It will identify the option which has fewest environmental impacts, but in practice it may be cheaper to do the “dirty” option and plant a large number of trees. Alternatively, there could be social issues as to why one option, although less “green” may be more acceptable to the public.

Decision making using life cycle assessment is further complicated by the varied nature of environmental impacts. Assessment across multiple impact categories may raise conflicting results. A system for producing electricity may have low greenhouse gas emissions but destroy a river. Likewise, disposal of a product in one way may cause high greenhouse gas emissions and another way may send large volumes of waste to landfill. Value judgements are therefore required. Life cycle assessments are not able to quantitatively say whether sending waste to landfill is better or worse than emission of greenhouse gases or releasing chemicals into a river, but it does allow for the identification of such distinct effects and for informed decision making as to what compromises are needed.

Particular care is needed when a life cycle assessment is going to be used for comparative purposes with different studies. Comparisons between different studies can be misleading if different assumptions have been made in process modelling or the studies’ scopes have been defined differently. Commercially, there are different databases available for assessment data on particular materials. Use of a different dataset can give vastly different results for the same process [43]. This highlights the importance of using the same assumptions, where

possible, for comparing two alternative systems. Furthermore it is important that only products with the same function should be compared [44].

3.2 Phases of an LCA

3.2.1 Goal and scope definition

The first stage of conducting a life cycle assessment is to define an unambiguous goal. Simply put, the goal is the reason for the study. It needs to include what the study is trying to find out, the reason for doing it, its intended application, as well as the target audience and stakeholders [45].

The goal is important as it influences the decisions throughout the study, including system boundaries, the level of complexity and reporting requirements [35].

Once the goal has been defined, the next part of the LCA planning and definition stage is to define the scope of the study. This includes whether or not the study is comparative, which parts of the life cycle will be included, what the system boundaries are, the level of detail to which the study will report and what the “functional unit” of the study will be.

A 2008 study conducted for the Ministry of Research, Science and Technology, and the Ministry of Economic Development on the usage of life cycle assessment and thinking in New Zealand classified assessments undertaken into three categories [46]. Firstly is the “Stand Alone” category or studies with a single product or process investigated retrospectively to describe the product. The second category, “Accounting” included studies that were “comparative and retrospective,” in other words, those comparing more than one existing process. The third category refers to those that are “Change Oriented” which were described as being “comparative and prospective.” Studies on new products being proposed as greener replacements for traditional materials would fall into this latter category.

Life cycle assessment practitioners also make a similar, but subtly different distinction between attributional and consequential assessments. Attributional assessments are those in which environmental impacts are attributed to a certain

amount of product, material or function. Consequential assessments investigate how impacts will change when a system is altered and can be useful when impacts of multifunctional processes are difficult to attribute [47-49]. The goal of the study dictates which of these two approaches will best answer the research question [48].

Once the type of study has been defined it is important to define the system boundaries and extent of the study, for instance, whether it is cradle to grave, or cradle to gate.

Cradle to gate assessments (also called eco-profiles) are partial investigations of the life cycle. The system starts with extraction of raw materials from the earth and ends at the factory gate with a material or product ready to be transported and used [50]. In the context of plastics, this could be the production of pellets or granules which are ready to be processed into products via processes such as extrusion, injection moulding, compression moulding and thermoforming.

In cradle to grave assessments, the system also starts with extraction of raw materials from the earth, but in addition to production of the material, they also include the use phase of the material and its eventual end of life disposal, releasing wastes and emissions back to the earth. A true cradle to grave system has no product crossing the system boundary – wastes will be the only output [51].

The intended use of a product can be a significant contributor to its environmental impact. For instance, natural fibre composites have been found to (counter intuitively) have similar environmental impacts to glass fibre composites in certain applications, as the bulk of the environmental impact from manufacture is due to the glues and resins that form the matrix for the fibres, rather than the fibres themselves. However, when used in certain automotive applications, because the natural fibre composites are lighter they have the potential to reduce fuel usage and show a superior environmental performance across their full life cycle in these applications [35].

At the front end of a life cycle, decisions also need to be made regarding the definition of the cradle, the starting point for the process and the raw materials. For instance with first generation bio-based polymers made from plant crops there

are fertilisers and farm machinery used to grow the crops before they can be used as feedstock for the plastic production. Ideally, all inputs would be traced back to raw materials from the earth, but such a comprehensive study is often not practical [39]. The level of detail required for upstream processes is dependent on the goal.

Another crucial definition is the “functional unit” of the study. This is based on the intended use of the product. The functional unit is an amount of function, not an amount of product. For example, a functional unit for a paint could be protection of a square metre of wall for a certain amount of time [36]. It is not a volume of paint, as different surface coverings may require higher or lower volumes for the same function, and it is the environmental impact of the whole product system, with respect to its intended use that is being investigated.

For example, a study was conducted on the environmental impacts of Danish pork production for export to the United Kingdom to determine if food miles are a significant factor. The functional unit was “1 kg of Danish pork (carcass weight) delivered at the port of Harwich” [52]. Although the function of pork meat is to be eaten, the goal of this study was not to compare pork with other food, but to assess whether imported pork had a significant environmental impact from food miles. Thus the function in question was the supply, not the consumption of pork and this functional unit can be justified. If a study was to be conducted comparing the environmental impacts of Danish pork and tofu, then an appropriate functional unit could be the delivery of a certain amount of nutritional energy. For plastic materials that have a number of potential applications the production of a given amount of material such as 1 kg of plastic pellets or resin ready for processing into further products is a common functional unit on a cradle to gate basis [13].

From the functional unit, a reference flow can be derived. This is the amount of product or material that is required to fulfil the amount of function included in the functional unit. The reference flow should be expressed in terms of SI derived units. It is important that the functional unit and hence the reference flow are relevant to the goal of the study.

The final stage of scope definition is to define the level of data quality required to complete the goal, along with what the critical review process for the study will be.

3.2.2 Life cycle inventory Analysis

Life cycle inventory analysis (LCI) consists of modelling a product system as a series of unit processes and then collecting data for the inputs and outputs for each of these. The product system is all the activities associated with and required for the delivery of a function using a product. This may include raw material acquisition, production of the product, use of the product, recycling or re-use of the product, and disposal of waste, along with the energy supply and transport requirements for each of these [39].

Ideally the product system should be large enough that the only inputs are those that have had no prior human intervention between being taken from the environment and entering the system boundary and the only outputs are those that have no subsequent human intervention after being released to environment. Such inputs and outputs are called elementary flows [36]. This may not always be practical, and assumptions and simplifications may need to be made to the product system. Any assumptions must be clearly defined, justified and checked using a sensitivity analysis.

The product system is broken down into a number of unit processes or the smallest unit that data is collected for within an LCA. For each unit process that is identified, data for material and the energy inputs and outputs need to be collected and converted to be expressed in terms of the amount per reference flow.

Where a unit process has more than one function, for example more than one product, allocation is needed to attribute a portion of the inputs and outputs to each function.

The standards on life cycle assessment include a stepwise procedure for allocation as shown in Figure 5 [39].

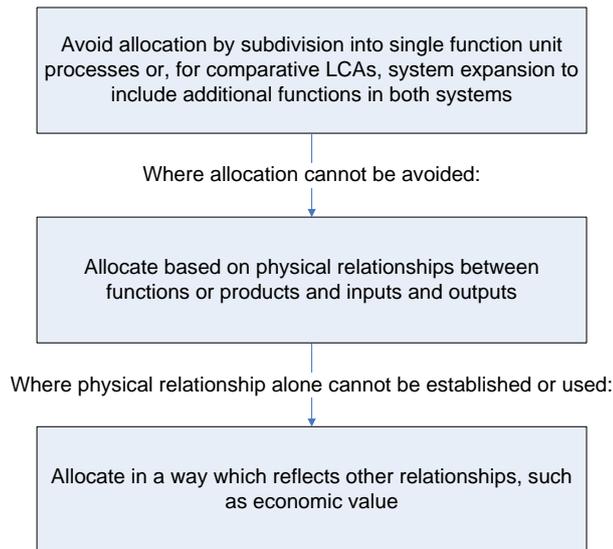


Figure 5: Stepwise allocation procedure from ISO 14041 [39].

Regardless of the allocation method used, the sum of allocated impacts should be the same as the unallocated impact [39]. If total emissions are known per mass of total products, then the allocated emissions per kg co-product A, E_A is:

$$E_A = F_A \times (E_U \times M_{UA}) \quad (1)$$

Where: F_A is the proportion of emissions to be allocated to co-product A (allocation factor).

E_U is the total emission per kg of all products.

M_{UA} is the total mass of all products per kg co-product A, i.e. total mass (M_U) divided by x_A .

x_A is the mass fraction of co-product A.

Total emissions for a unit process producing products A, B and C would be:

$$E_{Total} = E_U \times M_U = E_A \times M_A + E_B \times M_B + E_C \times M_C \quad (2)$$

Where M_U is the mass of total products and co-products produced .

E_A , E_B and E_C are the emissions allocated to each product, per kg of each respective product.

M_A , M_B , and M_C are the masses of each co-product produced.

This can be rewritten based on allocation factors as below.

$$E_{Total} = F_A \times (E_U \times M_{UA}) \times M_A + F_B \times (E_U \times M_{UB}) \times M_B + F_C \times (E_U \times M_C) \times M_C \quad (3)$$

Additionally, where an output from one unit process is partly co-product and partly waste, the ratio between these should be calculated so that inputs and outputs are allocated to co-products only [39].

ISO 14041 states that “the definition of the scope establishes the initial set of unit processes and associated data categories” that are contained within a product system [39]. The standard also repeatedly mentions the iterative nature of life cycle assessment studies. As inputs and outputs of unit processes are identified, and their raw materials traced upstream, the scope may need to be redefined to include further unit processes that had not initially been considered.

Data can be collected from a variety of sources. In some cases, particular processes may be well defined in literature, or it may be necessary to physically take measurements. In other cases, especially for a new process that has only been tested at laboratory scale, it will be necessary to make assumptions and to create a process model. These assumptions should be clearly stated and qualified and the model also should include alternative options.

As data is collected, it is necessary to check its suitability. When collecting data from literature, it is important to check for its regional and temporal closeness to the intended study, as different factories may have different operating efficiencies and processes can be improved or changed over time.

3.2.3 Life cycle impact assessment

Life cycle impact assessment (LCIA) is the processing of the raw data on energy and material flows into quantified environmental impacts. When done in accordance to ISO 14042, it consists of three compulsory elements and some optional elements [40]. The compulsory elements are:

- The selection of impact categories, category indicators and characterisation methods.

- Assignment of life cycle inventory results (classification).
- Calculation of category indicator results (characterisation).

The optional elements are normalisation, grouping, weighting and data quality analysis. Some of these optional elements contain value judgements that are not scientifically defined.

Generally, impact categories fall under the four following types: impacts on human health, impacts on natural environment quality, usage of natural resources and impacts on man made environments [53]. However, grouping impact categories into such types is not actually part of the ISO standard. ISO 14042 does not specify a list of impact categories, rather it gives criteria for what an impact category must have, such as an appropriate category indicator and characterisation factor [40]. The impact categories that are included within a particular study are dependent on the goal and scope of the study, and on the nature of the inventory data that has been collected. Some categories are climate change, stratospheric ozone depletion, acidification, eutrophication (both aquatic and terrestrial), human toxicological effects, ecotoxicological effects, photooxidant formations, biotic resources, abiotic resources, land use impacts, and other physical interventions such as noise or odour [54].

Each impact category has the following items associated with it: category endpoints; category indicators; relevant life cycle inventory results; a characterisation model and characterisation factors [45].

The characterisation model is a model of the environmental mechanism by which the inputs and outputs identified in the inventory phase cause changes to the environment, called category endpoints. This model is used to derive characterisation factors, the amount of change to the environment per unit of LCI input or output. Life cycle inventory results can be multiplied by characterisation factors to obtain into a category indicator, with common units for that category, called indicator results, according to the formula:

$$\text{Indicatorresult} = \sum([\text{Characterisation factors}] \times [\text{Relevant LCI results}]) \quad (4)$$

Each impact category will have a specific type of inventory result which can be identified as relevant to it, however, inventory results may affect more than one impact category.

Once the impact categories have been determined, the inputs and outputs from the inventory analysis need to be assigned to the relevant categories. Where inventory data does affect more than one category it needs to be decided whether the effects are from parallel or serial mechanisms. That is, whether the total amount will contribute to both categories, or if some of it will contribute to each.

The characterisation factors for each category can then be used to convert the assigned inventory results into common units as mentioned above. These units are based on the characterisation factors and do not always neatly fall into SI units [55]. These converted results are then aggregated to give the indicator result for each category across the whole life cycle [40]. This completes the compulsory elements of impact assessment.

The first optional element is normalisation. This consists of dividing the impact assessment results by a stated reference, and reporting these ratios. For instance, results for environmental impacts as a percentage of the total impact for each category for a given geography in a given year [45, 54].

The second optional element within life cycle impact assessment is grouping. This is grouping together related impact categories. Certain value judgements need to be made which will be guided by the goal and scope, but, are not scientifically derived. Any justifications and assumptions need to be recorded.

The third optional element is weighting which consists of aggregating the results of different impact categories based on their relative importance to give an overall score. This inherently involves value judgements, and the justifications need to be recorded. This step is not scientifically verifiable and should not be included in studies that are intended for making comparative assertions that are to be disclosed to the public.

3.2.4 Life cycle interpretation

Life cycle interpretation considers data collected from the life cycle inventory and life cycle impact assessments. It is used to identify any significant issues and evaluate the data for completeness, sensitivity and consistency. It should ultimately arrive at significant conclusions and recommendations. As with the other components of a life cycle assessment, this is part of an iterative process, both with respect to the elements that make up the interpretation phase and with regard to the other phases. As significant issues are identified and evaluated, it may be necessary to revisit the inventory and impact assessments and collect more data or improve models. It may even be necessary to refine or amend the goal and scope of the investigation.

ISO 14043 identifies a number of things that may be significant issues. These include inventory data categories, impact categories and the contributions of particular life cycle stages (such as unit processes or groups of processes) [41].

A completeness check consists of determining if any information that is relevant to the goal and scope of the study is missing or incomplete. If identified, it needs to be determined whether this information is necessary. If so, this feeds back into the LCI and LCIA, otherwise the reasons why it is not necessary need to be recorded and justified.

A sensitivity check is performed to determine the effects of uncertainty and the reliability of data on the results and preliminary conclusions. This includes the results of any sensitivity and uncertainty analyses that have been conducted as part of the inventory and impact assessment phases. The level of sensitivity analysis required is dependent on the goal and scope. If the life cycle assessment is to be used for “comparative assertions disclosed to the public,” a detailed sensitivity analysis is required.

A consistency check refers to checking that assumptions, methods and data are consistent throughout the assessment and with the goals and scope. ISO 14043 gives a checklist of questions relating to consistency of data quality across and within product systems, with respect to:

- data quality

- regional and temporal differences
- allocation rules and system boundaries
- application of the element of impact assessment

and that where there is an inconsistency within a product system, it is consistent with the goals and scope.

Drawing conclusions is done concurrently and "interactively" with the other elements of interpretation. A process for doing so is shown in Figure 6.

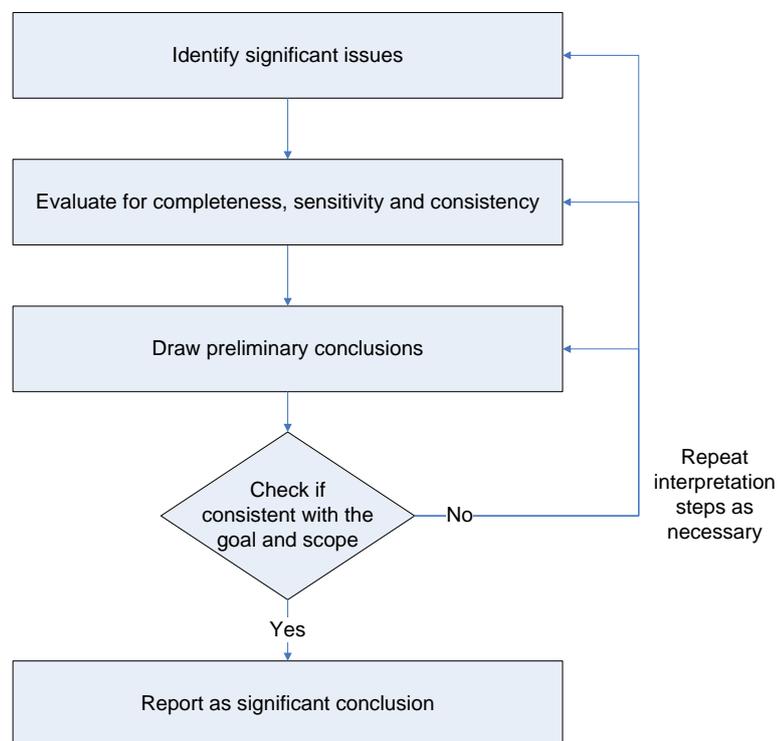


Figure 6: A logical sequence for drawing conclusion in life cycle interpretation [41].

ISO 14043 also provides guidelines for recommendations and reports. Recommendations should be based on final conclusions of the study and should reflect a logical and reasonable consequence of the conclusions. In addition, the report should give a complete and unbiased account of the study with full transparency as to value choices, rationale and expert judgements made in the interpretation phase.

3.3 A New Zealand context

In New Zealand much of the life cycle assessment work that has been performed has focussed on the primary sector [46], however, there has also been some work on the building industry, and recently, an extension into manufacturing [56].

New Zealand LCA and energy analysis work relating to the primary sector has investigated dairy, wool, meat, meat by-products, and the impacts from foodmiles from New Zealand products being exported overseas [57-60].

With regard to New Zealand agriculture, the predominantly pasture based system leads to smaller impacts than conventional overseas systems, even after international shipping to markets have been taken into account [58]. New Zealand dairy is more comparable to organic farming in Sweden and Germany, than conventional agriculture in those countries [61, 62]. However, current intensification of the NZ dairy industry may reduce this advantage [61]. Where low value by-products of agricultural activities have been used to make new products, the impacts of farming and meat processing have been allocated to the by-products on an economic basis [57].

There is no central database for New Zealand inventory data [46], however, some data is freely available for the building sector. In 1998 the Centre for Building Performance Research published embodied energy information for New Zealand building materials [63]. This information, along with an expansion to include greenhouse gases, was updated in 2001 and again in 2003 and used in LCAs of buildings [64-66]. In 2009 these were combined with data adapted from overseas databases to expand to more impact categories [67]. These have made use of the databases included in the Gabi and Simapro software packages. Likewise, for performing life cycle assessments, some New Zealand practitioners use those software packages, however others use excel spreadsheets and their own models [46].

3.4 Selected impact assessment models

Whilst life cycle assessment can be used to investigate a range of different impacts, many studies focus on energy or greenhouse gas emissions. As these two categories are given the most emphasis in literature a brief explanation of their

treatment within life cycle assessments is given here. These two categories are both global impacts. The amount of non-renewable energy in the earth is finite, and whilst different parts of the world will be affected differently by climate change all parts will be affected.

Table 1 and Table 2 show the characterisation methods used to relate inventory data to these two environmental impact categories.

Table 1: Life cycle inventory characterisation method for climate change [45].

Impact category	Climate change
LCI results	Emissions of greenhouse gases to the air (in kg).
Characterisation model	The model developed by the intergovernmental panel on climate change (IPCC) defining the global warming potential of different greenhouse gases.
Category indicator	Infrared radiative forcing (W/m^2).
Characterisation factor	Global warming potential for a 100 year time horizon (GWP100) for each greenhouse gas emission to the air (in kg carbon dioxide equivalents/ kg emission).
Unit of indicator result	kg carbon dioxide eq ($kgCO_2e$).

Table 2: Life cycle inventory characterisation method for non-renewable energy use.

Impact category	Non-renewable energy use
LCI results	Energy use.
Characterisation model	Cumulative energy demand (CED).
Category indicator	Non-renewable primary energy consumed.
Characterisation factor	MJ primary energy/ MJ delivered. New Zealand data obtained from [68].
Unit of indicator result	MJ.

3.4.1 Energy in life cycle assessment

ISO 14040 notes that “the calculation of energy flow should take into account the different fuels and electricity sources used, the efficiency of conversion and distribution of energy flow as well as the inputs associated with the generation and use of that energy flow [36].” Essentially this means including not just the energy used in the process, but the energy involved in producing and distributing that energy to where it is used.

One of the origins of life cycle assessment was in the energy analysis work of Ian Boustead [69]. In the methodologies he developed for the cradle to gate eco-profiles of plastics manufacture in Europe, energy is reported in the following categories [51]:

- Fuel production and delivery energy – This is the energy used in extracting primary fuel resources from the earth, any processing required as well as delivery to the consumer. This varies internationally, especially in the case of electricity which has different production efficiencies for different generation methods such as hydro, gas or coal.
- Energy content of delivered fuel – This is the energy used by the process itself and will vary based on the process.
- Transport energy – This is the energy involved in transport of inputs, intermediaries and products, excluding the transport of fuel which has been included above.
- Feedstock energy – This is the potential fuel energy of feedstocks that could be used as fuel, but instead are used as materials in the process. This is of particular interest in the production of petrochemical plastics, as not all fossil fuel used is burnt for energy, but some is incorporated into the polymer molecules. Feedstock energy is not the calorific value of the product, but represents the calorific value of raw materials.

Feedstock energy is not calculated or included for renewable materials that are not normally used for energy [70].

The above categories of energy can be expressed for each delivery method used in a system, for instance, electricity, oil fuels or other fuels. Alternatively they can be reported for each kind of primary energy extracted from the earth. In this latter case, electricity is then traced back into the fuels used to produce it [51]. When all of the above categories of energy are summed for all energy delivery methods and expressed in a common unit, the total is referred to as the cumulative energy demand (CED) or total primary energy extracted from the earth. This will often

include some primary energy from renewable sources and some from non-renewable sources.

3.4.2 Climate change and greenhouse gases in life cycle assessment

A life cycle approach is important when considering greenhouse gas emissions and their contribution to global climate change. For instance, in recent years there has been a growing awareness of “food miles,” or the distance food has travelled before reaching one’s plate. It is argued that transport requires fuel, which releases greenhouse gas emissions when burnt. Thus buying local food reduces greenhouse gas emissions. This argument, however, is flawed. Fuel required for transport is only one source of emissions in a product’s life cycle. Additionally, not all transport miles are equal. The amount of fuel (and hence emissions) for moving a given amount of product a certain distance varies for different forms of transport. International shipping is very efficient from a greenhouse gas emissions point of view (kgCO₂e/kg transported 1km). For instance, production and delivery of New Zealand lamb, even after accounting for transport from New Zealand to the United Kingdom, uses less energy and causes fewer greenhouse gas emissions than UK produced lamb [58].

Emissions of gases into the atmosphere are considered an inventory result in life cycle assessment. Relating the effect of these emissions to climate change is part of impact assessment and the characterisation model usually used is the model published by the Intergovernmental Panel on Climate Change (IPCC) which gives global warming potentials for different greenhouse gases based on the concept of radiative forcing [45].

Radiative forcing is a measure of the effect on the earth/atmosphere system’s energy balance due to alterations in factors that influence climate. It is quantified as “rate of energy change per unit area of the globe as measured at the top of the atmosphere” and is measured in watts per square metre [9]. Different gases cause different amounts of radioactive forcing, and have different lifespans in the atmosphere. Depending on the time span being considered, different gases have different relative potentials to contribute to global warming. The baseline normally used in life cycle assessment is GWP100, or the global warming potential over 100 years [45]. The potentials for each gas are expressed relative to

the contribution of carbon dioxide. So, while a life cycle inventory may have an amount of carbon dioxide, and an amount of methane, and an amount of nitrous oxides released, in impact assessment, these are aggregated together into combined amount. This combined global warming potential is expressed in carbon dioxide equivalents (kgCO₂e) representing the amount of carbon dioxide that on its own would have the same effect over the timeframe given.

Global warming potentials for major greenhouse gases are shown in Table 3. Each assessment report published by the IPCC provides updated global warming potentials based on improved models, however, the potentials published in the second impact report are widely used as the standard as they were adopted under the Kyoto Protocol and are used for compiling National Greenhouse gas inventories [9, 51, 71, 72].

Table 3: Global warming potentials on 100 year time span of major greenhouse gases[9].

Gas	GWP ₁₀₀ (kgCO ₂ e/kg) (as per IPCC second assessment report)	GWP ₁₀₀ (kgCO ₂ e/kg) (updated values for the IPCC fourth assessment report)	Comments
Carbon dioxide (CO ₂)	1	1	
Methane (CH ₄)	21	25	
Nitrous oxide (N ₂ O)	310	298	
Gases with indirect affects:			
Carbon monoxide		1.9	Global average value. Amount may vary depending on location.
Non-methane volatile organic compounds		3.4	Weighted average of a range of species.
Nitrogen oxides (NO _x)		Not available	Depends heavily on location and there is disagreement whether it is a positive or negative contribution.

Broadly speaking, air emissions from unit processes can be broken down into two categories: fugitive emissions and combustion emissions. Fugitive emissions are those from plant product streams, and in the absence of detailed data can be estimated based on known heuristics [73]. Combustion emissions are emissions

from the combustion of fossil fuels for providing process energy, and in the absence of detailed data can be estimated from energy demand using coefficients available from the Intergovernmental Panel on Climate Change or ones adapted for a specific country, such as New Zealand [68, 72].

Under the IPCC guidelines for producing national inventories, release of carbon dioxide from combustion or decay of recent biomass, removed from where it was grown, is assumed to be neutral. This is because it is assumed to be balanced by the carbon dioxide that was absorbed during photosynthesis [72]. Other emissions from agriculture, such as methane from livestock or nitrous oxides from fertiliser use are included under the IPCC guidelines. Methane is a much more potent greenhouse gas than carbon dioxide so conversion of carbon dioxide to methane via plant and animal should be included.

Regardless of one's views on whether or not anthropogenic climate change is myth or reality, there is a negative public perception regarding emission of greenhouse gases. If a product is intended to be marketed on a platform of sustainability or reduced environmental impact, an analysis of its greenhouse gas emissions is important. It is also important to remember that greenhouse gas emissions, even across the whole life cycle, are only one part of the ecological consequences of a product's use.

3.5 Conclusions

Life cycle assessment is a useful tool for analysing the environmental impacts of products and materials, and comparing different product systems. It can be used to investigate non-renewable energy use and greenhouse gas emissions, along with other environmental impacts.

The goal and scope of a study provide direction for defining system boundaries, collecting data on material and energy flows, relating that to environmental impacts and reaching conclusions. Cradle to gate assessments can provide some insight into the production of a material or product, but a full life cycle assessments consists of a cradle to grave analysis. All parts of a product's life cycle can contribute to environmental effects.

Life cycle assessment only provides information about environmental impacts, and needs to be combined with economic and social factors for decision making.

Energy use is an important part of life cycle assessment and should be reported transparently, with a distinction between direct energy use by a process and the energy required to produce and deliver that energy being made. Both kinds should be included in the analysis.

4 Life cycle assessment of other bio-based polymers

4.1 Introduction

As discussed in the Chapter Three, life cycle assessment is an internationally standardised method for modelling environmental impacts of a product specific function. A position paper on the use of life cycle assessment published by the European Bioplastics Association in late 2008 pointed out that there is no single life cycle assessment of biopolymers [44]. It is impossible to make a blanket statement such as the environmental impact of biopolymers is better (or worse) than those of traditional petroleum derived plastics.

There are different kinds of biopolymers, and even for the same polymeric material the manufacturing processes may vary. For instance, PHA is typically made by a fermentation process, in which microbes utilise a plant derived feedstock, however, there are various strains of microbes, utilising different plant feedstocks, which have been grown under different conditions. Furthermore, plastics are used for many different functions, and have several end of life disposal options. Composting of a material leads to different environmental impacts compared to the same material being incinerated or landfilled. For each system being investigated the choice of material, function, and how it is disposed of after use will contribute to a unique environmental profile.

The purpose of this chapter is threefold. Firstly, it serves to review the application of life cycle assessment to bio-based polymers. Secondly, common themes and impact categories are identified to form a basis of comparison between different studies. Thirdly, it identifies potential data sources for application in the life cycle assessment study of Novatein Thermoplastic Protein presented in subsequent chapters.

Bio-based polymers could be considered as sustainable as the carbon contained within them is taken from the atmosphere and not from depleting fossil fuel reserves [74]. The use of biomass feedstocks is seen as a strategy for achieving emission reductions [75]. Despite that, energy is still required for their production, and early analyses showed unfavourable comparisons with fossil fuel derived polymers they would replace [20, 76]. Since then there has been a vast amount of

work analysing bio-based polymer production and use by applying life cycle assessment methodology on a cradle to gate basis.

4.2 Cradle to gate assessment of selected bio-based polymers

4.2.1 Introduction

As some bio-based plastics are emerging technologies, with many potential applications and without established end of life disposal options, it is common to initially perform a cradle to gate based assessment on a proposed production system. Such studies can then be used to supply inventory data for a full cradle to grave assessment of a particular application. For example, a cradle to grave life cycle assessment of clamshell containers made from PLA obtained data for the production of the product from an earlier cradle to gate study [77, 78]. Without knowledge of the full product system, a cradle to gate assessment gives a meaningful foundation for the comparison of several bio-based polymer production systems. If the environmental performance at a materials level is not attractive there is a good chance that it will not be attractive at the product level either [13].

4.2.2 Petrochemical comparisons and eco-profiles

Since 1993, The Association of Plastics Manufacturers in Europe, now branded PlasticsEurope, has published environmental product declarations consisting of “eco-profiles” on major commodity plastics [79]. These are detailed inventory sets for the cradle to gate portion of a life cycle assessment, with data obtained from averaging inputs and outputs across multiple European plastics manufacturing plants. The methodology used in these was described in detail by Boustead (2005) [51], a key researcher in the field of life cycle assessment whose involvement stretches back to the origins of energy analysis in the seventies [69]. Boustead was careful to note that such profiles are not life cycle assessments, as they did not include the complete life cycle, but that they could be used as data sources when a full life cycle assessment was performed [51].

These PlasticsEurope eco-profiles have been referred to as the “most extensive and authoritative sources for LCA data on petrochemical polymers,” [80] and are used as a basis for comparison for the cradle to gate production of bio-based

plastics and petrochemical polymers in a number of studies [21, 23, 27, 42, 81]. The PlasticsEurope profiles also provide the life cycle inventory data on the production of plastic resins in the Ecoinvent database that is included with the commercial SimaPro™ software for conducting full life cycle assessments [77].

4.2.3 Polyhydroxyalkanoates

A cradle to gate life cycle assessment includes the entire production process, and use of different crop sources will therefore yield different life cycle inventory results. In addition, different fermentation technologies also give rise to different environmental impacts [24].

As such, just as there is not a single life cycle assessment for bio-based polymers, there is not a single cradle to gate life cycle inventory result for PHAs or PHB. However, there are a number of published studies looking at environmental impacts of different cradle to gate systems for its production from different feedstocks. Earlier studies concentrated on fossil fuel usage and greenhouse gas emissions, however, later studies have expanded the analysis to include other environmental impact categories [21, 24, 82]. Additionally some researchers have referred to work which has shown that non-renewable energy use has strong correlations with other impact categories and is therefore a good starting point for comparisons between systems [27, 83].

As the production of PHA is yet to be implemented on a commercial scale cradle to gate inventory assessments are based on data from a variety of sources including pilot scale plants [25], engineering estimates of hypothetical commercial plants [20], computer models of processes [23], from literature [24], and from life cycle assessment databases [84]. This is in contrast to the PlasticsEurope eco-profiles which are based on empirical data gathered from actual commercial plants and averaged across the industry [51].

Whilst earlier published applications of life cycle assessment to PHA cast doubts on its environmental credentials, later studies have demonstrated production systems with improved environmental profiles [81]. Additionally inconsistencies in allocation procedures were identified in a comparison that found that corn grain derived PHA required more fossil fuel energy than the equivalent amount of

polystyrene it would replace [20, 24]. Table 4 outlines published cradle to gate studies of various PHA production systems. Some of these reported a range of values for impact categories such as non-renewable primary energy use and greenhouse gas emissions.

The fermentation and recovery process is particularly energy intensive, contributing to the majority of the non-renewable primary energy demands and is the primary contributor to most environmental impacts, the exceptions being photochemical smog and eutrophication [20, 23, 24].

One method of reducing the environmental impacts of PHA production is to utilise renewable energy for the fermentation and recovery processes. It has been proposed that the production of PHA can be integrated into South American sugar mills. The mills described produce both cane sugar and ethanol and derive the energy used in mill processes from the biological feedstock entering the mill. They demonstrated that there is enough capacity in the mill's energy production from this biomass to also supply energy for a PHA fermentation plant [25].

The choice of fermentation feedstock also affects environmental impacts. A comparison between using soybean oil and corn glucose favoured production from soy with regard to energy consumption and carbon dioxide emissions. This was partially due to the higher carbon content per mass of soybean oil compared to glucose [23].

Table 4: A summary of the key findings of cradle to gate studies on various PHA production systems.

Biomass feedstock	Production system	Non-renewable primary energy and greenhouse gas emissions	Significant conclusions/findings
Corn	Fermentation of corn sugars [20].	Not stated.	System requires more fossil fuel per kg of polymer than for the production of polystyrene.
	Direct production in transgenic plants [28].	3.8 kgCO ₂ e/kg	System has higher net greenhouse gas emissions per kg than the production of polyethylene.
	Direct production in transgenic plants with energy recovery from combustion of residues [28].	-2.5 kgCO ₂ e/kg	System has lower net greenhouse gas emissions per kg than the production of polyethylene.
	Fermentation of corn sugars [24].	69 – 107 MJ/ kg 1.6 – 4.2 kgCO ₂ e/kg	Changing fermentation technology can reduce non-renewable energy needs and emissions from earlier systems [20].
	Integrated production of direct production in transgenic plants and fermentation of corn sugars energy recovery from combustion of residues [24].	17.8 – 31.5 MJ/kg -0.28 – -1.9 kgCO ₂ e/kg	Integrated system compares favourably with non-integrated system with regard to non-renewable primary energy use, global warming, photochemical smog, acidification and eutrophication.
	Fermentation of corn sugars, with process energy supplied by stover from additional corn crops in cogeneration plant [84].	2.5 MJ/ kg -2.3 CO ₂ e/kg	System has significantly reduced non-renewable primary energy use and net greenhouse gas emissions than earlier systems or petrochemical comparisons.
	Sugar Cane	Gate to Gate production via fermentation of sugars within self powered south American sugar mill [25].	Not stated.
Fermentation of sugars [21].		41.4 MJ /kg 2.6 kg CO ₂ e/kg	System compares favourably with production of polypropylene in all major categories and with polyethylene in all except marine ecotoxicity, acidification and eutrophication

Biomass feedstock	Production system	Non-renewable primary energy and greenhouse gas emissions	Significant conclusions/findings
Soybean	Fermentation of oil [23].	50 MJ/ kg 0.26 kg CO ₂ /kg	System requires less non-renewable energy and greenhouse gas emissions than corn grain system from or production of LDPE, HDPE, PP, PS and B-PET [20].
Industrial Wastewater	Mixed-culture fermentation [26].	Not stated.	System produces higher non-renewable CO ₂ emissions than from production from soybean oil but can be used to treat chemical oxygen demand [23].
Black Syrup	PHA from “black syrup” residues left after bioethanol production from corn stover [81].	Not stated.	System produces slightly higher greenhouse gas emissions than other PHA systems, but uses less total fossil energy than production of PS, LDPE, PET or PP.
Dairy	Fermentation of cheese whey [82].	Not stated	System had similar impacts to corn grain, but less than transgenic corn.

PHA can also be produced directly in transgenic corn and then extracted from the stover, eliminating the need for fermentation. However if this extraction is done with fossil fuel derived energy, this method still leads to a cradle to gate greenhouse gas emissions greater than that for the production of polyethylene [28]. This is partly due to steam requirements in the extraction process being four times higher [82]. On the other hand, should the biomass residues left over after extraction be used for energy production, the greenhouse gas profile is better than that of polyethylene production [28]. The integration of both corn grain based production via fermentation and production from stover, with energy recovery from residues, gives a process that has smaller impacts from cradle to gate when compared with earlier PHA production systems in terms of non-renewable energy use, global warming, photochemical smog and acidification, but not eutrophication [24].

When greenhouse gas and primary energy reductions are evaluated per area of land used for feedstock cultivation, production of PHA ranks badly against biofuels production, PLA, thermoplastic starch and natural fibres for use in petroleum based plastic composites [80].

Some recent work has also investigated the production of PHAs from wastewater streams using a mixed culture. High energy demands for the fermentation process are still found to be a significant contributor to non-renewable greenhouse gas emissions, but the need for farming is eliminated [26].

The various published cradle to gate studies on PHAs have shown that despite utilising a renewable feedstock, their energy intensive production can cause significant environmental impacts. Production systems can, however, be designed and optimised so that the cradle to gate eco-profile compares favourably with petroleum derived polymers.

4.2.4 Fermentation to produce a monomer- PLA

Polylactic acid or polylactide is a polymer that is also made from biological feedstock via a fermentation process. A carbon source, such as dextrose from corn, is fermented producing lactic acid, which is polymerised into PLA. As with PHA various feedstocks can be used, but commercially corn grain is preferred [19]. Compared with the available literature on PHA, life cycle assessment studies of PLA are scarce. An initial eco-profile for a commercial process in Nebraska by Cargill Dow was published in 2003, based on engineering estimates of the plant's performance. An update was published in 2007 which showed that the 2006 production system used 27.2 MJ fossil energy and emitted 0.27 kgCO_{2e} per kg of PLA [78].

As with PHA the bulk energy use (and hence the environmental impacts associated with energy production) is due to fermentation and downstream processes that convert bio-derived feedstock into useable polymers [42]. If this energy is derived from conventional sources, PLA requires more fossil energy than that used as process energy to produce polyethylene, polystyrene polypropylene or PET production. These petroleum based polymers, however, also require fossil fuels as feedstock, and when this is added to the amount required for fuel, the total is more than the amount required by PLA [42]. The PLA system also has a similar contribution to global warming potential to that of the production of low density polyethylene or polypropylene. The use of renewable energy from wind or biomass can reduce both non-renewable energy demand and global warming potential [42, 78]. Furthermore using a biorefinery,

where biomass is converted into multiple products (analogous to the multiple outputs of an oil refinery) can decrease non-renewable energy needs for PLA production [85].

Despite these significant energy needs, some reviewers persist in claiming that PLA is inherently a carbon neutral material across its whole life cycle as the carbon released as it degrades came out of the atmosphere [74].

It has also been demonstrated that PLA could be produced from the fermentation of municipal food waste [86]. Such a system would not require extra land for the production of raw materials, however, it is still energy intensive. One way to counteract the energy requirements would be to also utilise the municipal food waste to generate energy to power the process [86].

When primary energy and greenhouse gas reductions per land area used are considered, PLA performs well against PHA and biofuels, but not as well as natural fibre composites of petroleum based plastics [80].

4.2.5 Natural polymers

Direct modification of polymers found in nature is an alternative to manufacturing bio-based plastics from biomass via fermentation. Thermoplastic starch is commercially available for a number of applications and its use to displace petroleum derived plastics has been shown to produce energy savings [12]. Energy is still used in crop production and starch extraction, but there is no energy intensive fermentation step. Much of the work involving life cycle assessment of starch materials has been conducted by manufacturers of these materials in Europe and summaries of the findings can be found in a number of review chapters in books [11-13].

Starch based materials are also combined with petroleum based copolymers to improve properties and increase the number of applications they can be used for. In such cases, the environmental impacts generally decrease with a decreasing proportion of synthetic polymer [11]. When making comparisons one needs to remember the importance of functional equivalence. Starch materials without the petrochemical co-polymers are not able to fulfil all the functions that the blends can and are therefore not functionally equivalent. This means that starch based

blends should be compared with the pure petrochemical polymers they can replace, rather than with pure starch thermoplastics.

Unlike PHA and PLA, where much of the work has focussed on different production technologies, for starch there is a body of work considering different end-of-life disposal options. In fact, it is difficult to find a cradle to gate only profile for starch. Even where the use phase has not been defined, different disposal options are included in the analysis. Such analyses could potentially be defined as “cradle to gate plus grave” assessments. Although some deal with products, some also deal with materials that could be used for a number of applications [13]. This potentially highlights that the biodegradability of starch based materials are just as much of a motivation for their use as its renewability.

Further discussion of cradle to grave life cycle assessments of products made from bio-based plastics, including starch based material, is included later in this chapter.

Life cycle assessments of other bio-based polymers are rare. Natural rubber is a polymer that has been used commercially for decades. Whilst showing up in comparative life cycle assessments for floor coverings it was not clear in that paper where inventory data were obtained [87]. A qualitative investigation into environmental impacts across the life cycle of disposable latex rubber gloves used in US hospitals raised interesting questions about the flow of resources between developing and developed countries. Whilst not a formal life cycle assessment, this identified the impacts of monoculture plantations on local food production and forests, workers rights, health and safety and wages, as materials are produced to support the affluent lifestyle of the developed world [88].

4.2.6 Trends, observation and criticism for cradle to gate profiles

For both the production of PHA and PLA the energy used in fermentation and downstream processing is significant and can be a key contributor to non-renewable primary energy use and climate change. The use of renewable sources to provide process energy improves the cradle to gate eco-profiles of these bio-based polymers. However, the possibility that the eco-profiles of petroleum derived plastics can also be improved using renewable sources for process energy has not been explored. This begs the further question as to which provides a

bigger environmental burden, the feedstock or the energy used to process it. Consider the combinations of energy and feedstock sources shown in Figure 7.

Renewable energy	Conspicuously absent	Improved bio-based plastics (PHA, PLA etc. with windpower or combustion of biomass)
Fossil energy	Conventional plastics (polyethylene, polypropylene etc.)	Bio-based plastics (PHA, PLA, TPS etc.)
	Fossil feedstock	Renewable feedstock

Figure 7: Possible combinations of renewable and non-renewable feedstock and energy.

Earlier studies compared the two bottom options and found moving to a renewable feedstock did not necessarily confer a significant environmental improvement. The proposed solution is to move from the bottom right to the top right with renewable energy and feedstock which does yield reduced impacts when compared with the bottom left. However, plastics in the top left would also provide a meaningful comparison with the improved bio-based plastics. The implication is that renewable energy for energy intensive biopolymer production could be used for synthetic polymer production realising an environmental benefit.

It has been suggested that it is more environmentally friendly to use renewable energy to displace existing fossil energy use than to make new forms of plastic [89]. However, this observation does not address other impact categories, such as land use. It has been shown that some bio-based polymers are more effective at reducing greenhouse gas emissions than the production of biofuels per area of land used [80]. Because cradle to gate assessments do not include environmental impacts in other parts of a product's whole life cycle, they do not provide the complete picture.

Although some bio-based polymers have been around prior to most petrochemical polymers, the technology for producing bio-based thermoplastics that can serve as functional replacements for petroleum derived polymers is relatively new. This is in contrast to the petrochemical industry, which is largely mature. Whilst reductions in environmental impacts with conventional plastics are possible as technologies improve these are likely to be small and incremental, however, the manufacturing processes for bio-based polymers are new and have significant scope for future improvements, including but not limited to the aforementioned use of renewable energy [50, 90].

4.2.7 Waste materials as a feedstock

Second generation bio-based polymers are those utilising feedstock from waste streams. It was previously shown that PHA from industrial wastewater contributed more to global warming than a soy-crop based system [26] and PLA from municipal food waste required more primary energy than corn grain based production [86]. Of particular interest is that in both cases the waste was treated as an input and the goal and scope did not extend upstream to include the processes that generated it. The waste material did not carry any environmental impacts of the process, even though it was now being used to make a product. This is a potential precedent for consideration in the life cycle assessments of other second generation bio-based polymers.

4.2.8 Results of cradle to gate assessments

Table 5 shows data for selected plastic production systems that will be used for cradle to gate comparisons with a second generation bio-based polymer made from bloodmeal in later chapters. It should be noted that such a comparison does not constitute a life cycle assessment. A full life cycle assessment should be based on systems of functional equivalence examined from cradle to grave [90]. However, comparisons are often made between production systems of different materials that could fulfil the same function. This allows initial estimation and speculation as to what may be relevant in a comparison over an entire life cycle.

Table 5: Cradle to gate primary energy use and greenhouse gas emissions for selected bio-based polymers and petroleum based polymers.

Material	Non-renewable primary energy use (MJ/kg polymer)	Greenhouse gas emissions (kg CO ₂ e/kg polymer)
PLA from corn grain, conventional process [42].	54.1	1.8
PLA from corn grain with wind energy [78].	27.2	0.27
PHA from corn grain without energy recovery (then current metabolix via mass allocation) [24].	66.0	1.92
PHB from corn grain using biomass energy from corn stover [84].	2.5	-2.3 ²
Thermoplastic starch assumed incinerated (cradle to gate + grave) [13].	25.4	1.14
Polypropylene [91].	73.0 ³	2.00
Low Density Polyethylene [92].	72.3	1.89
High Density Polyethylene [93].	76.0	1.96

4.3 Cradle to grave assessments of bio-based polymer products

Whilst the above cradle to gate studies provide interesting comparisons on the production of different materials, they do not tell the full story. Environmental impacts from transport, use and disposal should also be considered when comparing specific bio-based plastic products to petroleum based alternatives. As each application is different and will have system boundaries that are only relevant in the cases being compared it is not reasonable to assume that results from a life cycle assessment of one product system will be the same for others of the same material. However, some generalisations can be made on cradle to grave

² A negative value for global warming potential here represents the CO₂ being removed from the atmosphere during corn cultivation as exceeding emissions during the manufacturing process. As this value is only for the cradle to gate process, return of this carbon to the atmosphere is outside of the reported scope. For a full cradle to grave process, a negative global warming potential could represent carbon sequestering in the earth, or conversion of gases with higher global warming potential to ones with lower global warming potential.

³ In the case of the petroleum based polymers, not all of this primary energy from the earth is used as fuel, around 2/3 of it represents oil feedstocks that become part of the polymer.

analysis and it can be deduced that bio-based plastics can offer advantages over their entire life cycle in some product systems.

Although life cycle assessment identifies impacts, human judgement is still needed when comparing alternatives that rank differently across various impact categories. For example, a multilayer film for food packaging composed of thermoplastic starch and PLA has been shown to compare favourably with the conventional petroleum derived multilayer film with regards to non-renewable energy and greenhouse gas emissions. However, the conventional film has a smaller contribution to eutrophication [94]. The decision then needs to be made whether to choose the product that releases more greenhouse gases or the product that causes more damage to land and waterways.

In another example, thermoplastic starch-based loose fill packaging material has been shown to have smaller impacts compared to expanded polystyrene in terms of winter smog, air toxicity, carcinogenicity, energy use, global warming, acidification, ozone creation and heavy metals, but worse salinisation and deposited waste [13, 95]. Different people, organisations and societies may have different preferences, meaning value choices must be made when interpreting the collective contribution of all impacts [40]. In that case it was concluded that the starch-based loose fill packaging was less damaging than expanded polystyrene [13].

In some instances, impacts stemming from the use phase can outweigh benefits from production and disposal, for example car panels made from PHB/natural fibre composites. Although having lower impacts for the cradle to gate production when compared to polypropylene and glass fibre composites it could replace, a higher mass of bio-composite is required to achieve the same material properties. This leads to increased fuel consumption over the life of the car, negating any benefits from using such a biomaterial for this application [27]. In contrast, the use of natural fibres to reinforce synthetic plastic matrices can lead to weight savings and hence fuel savings in some automotive applications [96, 97].

Re-use can also be a factor. An LCA of degradable plastic bags found reusable bags to have lower impacts across resource use, greenhouse gas emissions and

eutrophication than any single use bag, regardless of whether those single use bags are bio-derived, biodegradable or both [97, 98].

The use of fuel is also an important consideration in the transport of the materials. For example, consider clamshell containers made from PLA, PE or PET and used for packaging strawberries. It was found that the distance travelled by truck from contributed significantly to environmental impacts when systems utilising the different materials were compared [77]. This shows that not only does renewable feedstock fail to guarantee environmental friendliness; even the use of renewable energy in production processes can be negated by activities required by other parts of the life cycle.

Material disposal also influences the outcome of a cradle to grave study. In heterogeneous waste streams, which include polymers, the inherent properties of a bio-based and biodegradable polymer can be advantageous. For instance, the use of compostable starch bags for collection of compostable waste has eliminated the need for separation and contamination by petroleum based plastic [99]. Similarly, a system where disposable cutlery made from thermoplastic starch is composted along with food waste has been shown to compare favourably with alternatives where conventional plastic cutlery is either landfilled or incinerated along with the food waste [100]. However, compostable polymer can cause problems if they are mixed with conventional polymers that are to be recycled.

Bio-based polymers that are biodegradable offer new recovery and disposal options, which can be evaluated by life cycle assessment [90]. It is not fair to always assume bio-based plastics will be disposed in the same way as petroleum based polymers. For instance if, landfilling without biodegradation is assumed, there is not necessarily a reduction in greenhouse gas emission in using bio-based plastics. A PLA yoghurt delivery product was shown to have equivalent greenhouse gas emissions to polypropylene if both are landfilled at the end of life [101]. If a different end-of-life scenario was considered the results would have been different, as significant emission and energy credits can be accrued if polylactide is disposed of by composting and the compost is used in agriculture [102].

Landfilling can lead to advantages for petroleum derived polymers, as carbon is not released into the atmosphere, whereas biodegradation of bio-based plastics in a landfill situation can lead to methane production. This methane represents a higher global warming potential than the carbon dioxide that was removed from the atmosphere to produce the bio-based plastic [97].

Assuming that non-renewable energy use in the production of bio-based plastics can be limited, it makes sense to use these polymers in cases where a product is only used once and the material property requirements are less stringent. If, however, long term use is intended, biodegradability is less essential, perhaps even a problem. Ways in which a product can save or reduce energy consumption during can be more important than the impact of production.

4.4 Conclusions

As seen in the previous two chapters, bio-based and biodegradable polymers have been proposed to address environmental concerns related to plastics. A review of the literature on life cycle assessments of various bio-based polymers was performed to identify common themes in the life cycles of bio-based plastic and determine a basis for comparison for a new material.

A biological feedstock alone does not ensure that production of a bio-based plastic uses less fossil resources than conventional commodity plastics they could replace. On a cradle to gate basis, bio-based polymers made via fermentation can use more energy. If the energy is generated from fossil sources, then it can also be a significant contributor to non-renewable energy use and greenhouse gas emissions. For example a production system for PHA has been shown to require 66.0 MJ non-renewable energy and release 1.92 kg CO₂e greenhouse gases per kg polymer and a system for producing PLA has been shown to require 54.1 MJ and release 1.8 kg CO₂e per kg polymer when using conventional energy. This is more than the primary energy consumed for process energy when producing conventional polymers such as polyethylene or polypropylene. In contrast, a modified natural product like thermoplastic starch requires no fermentation step and can reduce primary energy demand when replacing petroleum based plastics. Using renewable sources such as windpower to provide process energy can also reduce the non-renewable energy and greenhouse gas emissions of bio-based polymers.

When commercial processes for the manufacture of bio-based polymers are still in development, it is common to base life cycle assessment data on engineering estimates and model processes, rather than empirical data collected from manufacturing plants. This potentially introduces error, as comparisons are made between theoretical processes and real ones.

Furthermore, whilst dedicated life cycle assessment software applications are available, which can contain life cycle inventory databases on existing processes, such packages are not typically used for initial cradle to gate assessments of new processes. The results of cradle to gate assessments can be used as inputs in such software when cradle to grave systems are being analysed.

A cradle to gate assessment is a common first application of LCA methodology for new bio-based polymers, which can later be used to analyse entire product systems. A cradle to gate analysis should report at least non-renewable primary energy use and greenhouse gas emissions. Cradle to grave assessments are more complex as each product system and disposal method is unique. Transport, energy consumption in the use phase, and various disposal options at the end of a products life all also contribute to the total environmental impacts of using a product.

5 Inventory of data on unit processes in the production of Novatein Thermoplastic Protein

5.1 Goal definition

Novatein Thermoplastic Protein (NTP) is a new bio-based polymer being developed at the University of Waikato using the protein content of bloodmeal as a feedstock. The motivation for bio-based plastics is the use of renewable resources to reduce dependence on non-renewable fossil fuels. However, the use of renewable feedstocks does not necessarily mean a product uses less fossil fuel in its production or over its entire life cycle.

Whilst using blood proteins from bloodmeal makes use of a renewable feedstock that does not compete with human food supply, there are other raw materials used to denature and plasticize this feedstock. These require energy to manufacture and to transport to the plant. Energy is also used to compound the bloodmeal with these ingredients to produce a thermoplastic. Bloodmeal is made by drying blood, which is collected from abattoirs, after animals have been killed.

At this stage in development, a full product system does not yet exist for NTP. A cradle to grave study on a product made from the polymer is therefore not yet possible. Instead, a cradle to gate study was conducted with the following objectives:

- Calculate primary energy and greenhouse gas emissions data on the production of NTP.
- Identify the most significant contributions to impacts on a cradle to gate basis.
- Compare with cradle to gate production of other bio-based polymers.

This comparison is to be made against literature values for the cradle to gate production of a number of materials.

The intended application of this study is internal decision making by Novatein Limited. Specifically, a decision as to whether production of NTP can be justified

with regard to greenhouse gas emissions and non-renewable energy use. It is also intended to provide attributional cradle to gate greenhouse gas emission and non-renewable energy data for the production of NTP for use in future cradle to grave assessments. The assessment is not intended for use to make marketing claims of equivalence or superiority between a product made of NTP and another product that could fulfil the same function. This goal therefore does not fall under the definition of a “comparative assertion disclosed to the public [45].”

5.2 Scope

This assessment is primarily concerned with the production of a blood protein based biopolymer in a New Zealand context. The technology for converting bloodmeal into a bio-based polymer is being developed in New Zealand, and the company that has been established to commercialise the technology is based in New Zealand. It is feasible that the technology will eventually also be used overseas, and therefore some consideration will also be given to international blood processing. Impacts from using the polymer in a product and disposal at the end of the product’s life are not within the scope of this assessment.

5.2.1 Function

The function of the system being investigated is to produce thermoplastic polymeric material that can be processed by techniques such as extrusion and injection moulding into useful products, as a replacement for petroleum based polymers such as polyethylene.

Under ISO guidelines the functional unit of systems being compared should have functional equivalence [39]. The laboratory produced polymer has comparable mechanical properties to low density polyethylene (PE) and hence can be considered functionally equivalent to PE in many applications [17].

The functional unit is defined as the production of one kilogram thermoplastic material that can injection moulded into applications such as single use seedling trays. The reference flow will be one kilogram polymeric material.

5.2.2 System boundaries

Cattle farming consists of raising animals to meet human needs for food. In addition to carbon dioxide and sunlight absorbed by plants grown as feed, inputs include fuel and electricity used in farm activities and fertilisers used to increase plant growth. Cattle are ruminants and their digestive system is a source of methane, a potent greenhouse gas.

Meat processing consists of slaughtering animals and turning their body parts into useful products. At the rendering plant, blood is dried into bloodmeal powder. Fat, offal, hides and blood are all products from abattoirs, which require further treatment to be turned into useful products. Although rendering is an essential part of meat processing operations, it is considered as a separate unit process in this analysis.

In addition to bloodmeal powder, several other additives are used in NTP to enable the protein chains to undergo thermoplastic processing. The production systems of each of these materials constitute further unit processes.

The system boundaries and unit processes for which data is collected are shown in Figure 8.

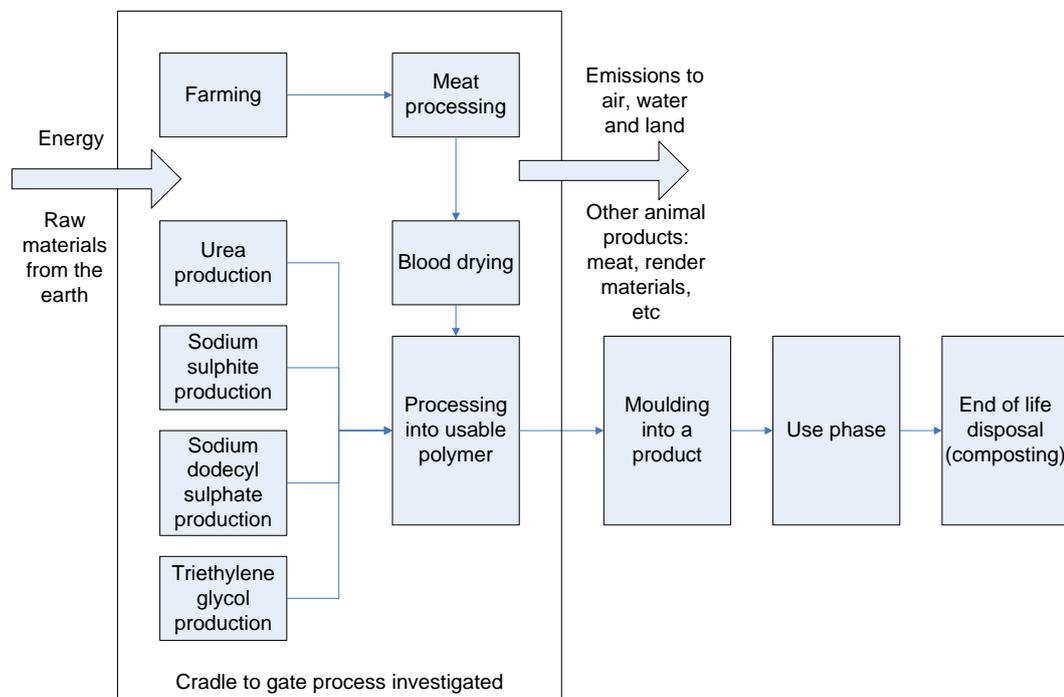


Figure 8: System boundaries for Novatein Thermoplastic Protein.

These unit processes are not all conducted at the same geographical location. Additional energy is required for the transport of intermediates between where they are made from raw materials from the earth, and where they are used to manufacture NTP.

Farming and meat processing constitute multifunctional processes and therefore allocation is needed to divide impacts between products. A variety of different allocation methods are considered in the next chapter.

5.2.2.1 Omission of life cycle stages, processes or data needs

Consistent with the goal that has been defined, this assessment does not include moulding NTP into a product, the use of that product, or disposal at the end of its life. The earlier review of life cycle assessments of other bio-based polymers showed that cradle to gate assessments are a common application of life cycle assessment to these materials and can be used to build cradle to grave assessments in the future.

Also omitted from this analysis is the energy used in construction of the proposed Novatein Thermoplastic Protein facility. It is assumed that sustainable building techniques and materials will be used such that the use phase of the facility will be the only significant contribution to environmental impacts over the building's life.

5.2.3 Electricity production in New Zealand

Electricity can be generated in a number of different methods, from renewable or non-renewable sources, each with different efficiencies and environmental impacts. The mix of electricity production methods used varies internationally and therefore the primary energy required to deliver the same amount of electricity will vary also [51].

In New Zealand, around 65% of electricity generated comes from renewable sources such as hydro electricity, geothermal and wind power [103]. This means that greenhouse gas emissions and non-renewable energy requirements related to electricity usage from the national grid are lower than for other countries relying on predominantly coal or oil based generation.

Such a mix causes variability from year to year. Hydro and wind generation are both dependent on local or regional weather conditions (rainfall and wind respectively) and as such the amount of electricity that can be provided varies seasonally and annually. Thermal generation from fossil sources such as coal and gas supplements New Zealand's demand. Variability in renewable supply and demand as well as commissioning of new power plants means that the exact mix of generation varies considerably.

Two electricity generation assumptions are considered in this analysis. Firstly, it is assumed that electricity comes from the New Zealand grid and has the impacts of average production of New Zealand electricity. The second case is a worst case assumption, whereby New Zealand renewable generation is assumed to be operating at capacity, and therefore additional demand is met by increased coal generation. This will also provide a worst case if NTP is manufactured overseas.

Primary energy and greenhouse gas coefficients for the supply of New Zealand electricity are available from the Agribusiness group [68, 104]. Electricity requirements of a process can be multiplied by these coefficients to convert into primary energy and associated greenhouse gas emissions. For average New Zealand electricity in 2008, the factor is $2.36 \text{ MJ}_{\text{primary}}/\text{MJ}_{\text{delivered}}$ or $8.50 \text{ MJ}_{\text{primary}}/\text{kWh}_{\text{delivered}}$ for primary energy and $0.06597 \text{ kgCO}_2\text{e}/\text{MJ}_{\text{delivered}}$ or $0.2375 \text{ kgCO}_2\text{e}/\text{kWh}_{\text{delivered}}$ for greenhouse gas emissions [68].

The method used to calculate these factors includes an allowance for upstream energy for extracting fossil fuels and makes use of data from the New Zealand Energy Data File [103]. The split between renewable and non-renewable primary energy used to produce electricity in 2008, also based on the New Zealand Energy Data file, is shown in Table 6. The ratio between total primary energy for non-renewable generation from coal and gas ("A" in Table 6) and for renewable generation ("B" in Table 6) was used to split the primary energy coefficient for average New Zealand electricity in 2008. This resulted in a non-renewable primary coefficient of $1.0 \text{ MJ}_{\text{primary}}/\text{MJ}_{\text{delivered}}$ and a renewable primary energy coefficient of $1.36 \text{ MJ}_{\text{primary}}/\text{MJ}_{\text{delivered}}$. That is, for each MJ of electricity used in New Zealand in 2008, 2.36 MJ of primary energy was consumed, 1.0 MJ from non-renewable sources and 1.36 MJ from renewable sources.

Table 6: New Zealand primary energy consumption for the production of electricity in 2008.

Generation type	Energy used to produce electricity (PJ/year) [103]	Primary energy coefficient for extraction of fuel [68].	Primary Energy used to extract and supply fuel, and produce electricity (PJ/year)
Coal	43.37	1.02	44.24
Gas	83.89	1.13	94.80
Total non-renewable (A)	127.26		139.03
Renewables (B)	189.8	n/a	189.80
Total (C)	317.06		328.83

Renewable generation is limited by natural factors and fluctuates seasonally. Until new generation methods are installed, the load on thermal power stations can be expected to rise as national demand increases [105]. Furthermore, New Zealand's largest thermal generation facility, Huntly, has switched from gas to predominantly coal [105].

In 2008, 15.96 PJ of the electricity produced in New Zealand was generated from coal [103]. If it requires 44.24 PJ primary energy/year to extract coal and generate this electricity (Table 6), a primary energy co-efficient of $2.77 \text{ MJ}_{\text{primary}}/\text{MJ}_{\text{delivered}}$ is obtained. This allows a theoretical “worst case” reference for New Zealand electricity supply, and also provides data for a consequential approach to electricity. This factor will be used as a proxy for overseas electricity, where generation methods are unknown.

The greenhouse gas emissions factor for New Zealand for lignite coal is $0.09789 \text{ kgCO}_2\text{eq}/\text{MJ}_{\text{primary}}$ [68]. This factor includes both combustion emissions and emissions associated with upstream extraction of coal. Based on this an emission of $0.271 \text{ kgCO}_2\text{e}/\text{MJ}_{\text{delivered}}$ can be calculated for New Zealand coal fired electricity generation.

In addition to average electricity, the primary energy and greenhouse coefficients published by Agrilink include factors for other fuels used in New Zealand such as diesel, coal and natural gas. These are also used in this analysis when estimating primary energy and greenhouse gas emissions for processes consuming those fuels. Factors used in this analysis are shown in Table 7.

Table 7: Primary energy and greenhouse gas coefficients for selected New Zealand energy delivery methods [68].

Delivered energy type	Non-renewable primary energy (MJ _{primary} /MJ _{delivered})	Renewable primary energy (MJ _{primary} /MJ _{delivered})	Total primary energy (MJ _{primary} /MJ _{delivered})	Greenhouse gas emissions (kgCO ₂ e / MJ _{primary})	Greenhouse gas emissions (kgCO ₂ e/ MJ _{delivered})
Electricity (2008 average)	1	1.36	2.36	0.02794	0.06597
Electricity using coal (2008 average)	2.77	n/a	2.77	0.09789	0.2712
Coal (Lignite)	1.02	n/a	1.02	0.09789	0.09985
Diesel	1.19	n/a	1.19	0.06880	0.08187
Natural gas	1.13	n/a	1.13	0.05395	0.06096

5.2.4 Criteria for inclusion and data requirements

Inputs included in this assessment are non-renewable energy for the production and delivery of materials included in the core process of producing Novatein Thermoplastic Protein (Figure 9). Outputs included are the product itself and emissions to air of greenhouse gases.

Total non-renewable primary energy use and greenhouse gas emissions for each unit process have been used to estimate total non-renewable primary energy use and greenhouse gas emissions for the cradle to gate system. Preference has been given to data from New Zealand and from sources from within the last 10 years.

First consideration is given to the process for processing of bloodmeal into a thermoplastic protein. Next, the production of the non-bloodmeal additives is described as these are required regardless of assumptions about bloodmeal supply. The upstream production of bloodmeal from blood is then considered. Lastly, the impact of farming and meat processing leading to the supply of blood is included.

5.3 Conversion to Novatein Thermoplastic Protein

5.3.1 Process overview

The temperatures and pressures involved in extrusion cause excessive cross-linking and protein denaturing in the absence of plasticizers [17]. Proteins in

bloodmeal are already highly denatured, with many interactions between polypeptide chains. The interactions between chains need to be overcome to allow melt processing such as extrusion, but on heating bloodmeal alone, crosslinking occurs before these interactions are overcome.

To convert bloodmeal into a thermoplastic material it is first mixed with a selection of reducing agents, protein denaturants and plasticizers that disrupt the interactions between the polymer chains. This increases chain mobility at lower temperatures, allowing thermoplastic extrusion.

A commercial feasibility study has been conducted on a hypothetical processing plant producing Novatein Thermoplastic Protein. In the proposed large scale process, water is heated by a gas heater, and then mixed with the denaturants and plasticizers in an agitator. This solution is then added to milled bloodmeal and mixed in a ribbon mixer, before being fed through an extruder. The extruded polymer is palletised, and then cooled before loading [106]. A block flow diagram for this process is shown in Figure 9.

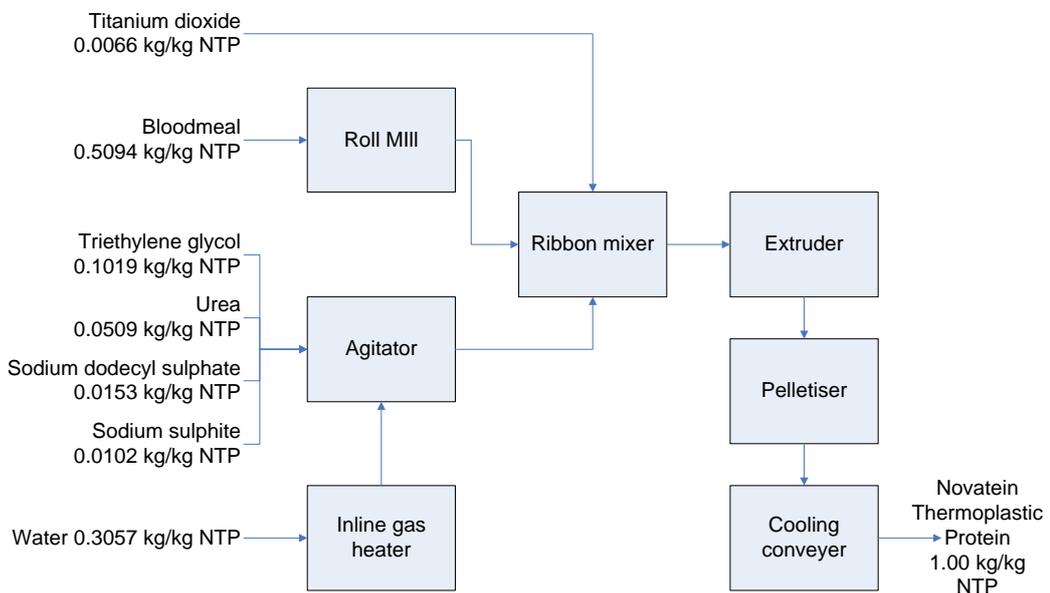


Figure 9: Proposed commercial process for the production of Novatein Thermoplastic Protein.

5.3.2 Material input

The commercial feasibility study was based on an early recipe which has since been modified with additional plasticizer. The formulation of the updated recipe is

shown in Table 8 in both mass fractions and in parts per hundred bloodmeal (pph_{BM}) as used in the laboratory.

Table 8: Material inputs for the production of Novatein Thermoplastic Protein.

Material	Mass fraction (kg/ kg NTP)	pph_{BM}
Water	0.3057	60
Urea	0.0509	10
Sodium dodecyl sulphate	0.0153	3
Sodium sulphite	0.0102	2
Triethylene glycol	0.1019	20
Titanium dioxide	0.0066	1.3
Bloodmeal	0.5094	100
Novatein Thermoplastic Protein	1.00	196.3

5.3.3 Energy input

Table 9 shows the energy requirements of the process described in the commercial feasibility study. It is assumed that the change in recipe has a negligible effect on electricity and gas requirements.

Table 9: Delivered energy requirements for the production of Novatein Thermoplastic Protein [106].

Electricity	kWh/year	MJ/kg
<i>Major process units as shown on the BFD</i>		
Roll mill	12873	0.0128
Agitator	522	0.0005
Ribbon mixer	19575	0.0194
Extruder	826048	0.8188
Pelletizer	97925	0.0971
Conveyer belt (cooling)	21000	0.0208
<i>Transport operations within plant</i>		
Pneumatic feeders	78299	0.0776
Pump	193	0.0002
Conveyer belt (feed)	420	0.0004
<i>General</i>		
Scrubber	2450	0.0024
General operations (eg lights, control panels etc)	23284	0.0231
Total electricity	1082589	1.073
<i>Natural gas</i>		
	(GJ/year)	(MJ/kg)
Inline gas heater	288	0.0793

5.3.4 Outputs

The most significant output of the proposed facility is the product itself. There are no useable co-products or by-products of the conversion of bloodmeal into bio-based polymer. Thus all of the environmental impacts of this unit process can be attributed to NTP. The process does not include any other outputs, however, some waste and emissions are to be expected.

5.3.4.1 Emissions to air

The main source of greenhouse gas emissions for the core unit process is assumed to be the production and delivery of process energy, however, when bloodmeal is processed with chemical denaturants and extruded, volatiles are released. The plant design proposed in the commercial feasibility study includes air scrubbers and filters to keep the air in the plant at a healthy level, but the mass of emissions are assumed to be negligible on the scale of the mass balance [106].

A rule of thumb for calculating fugitive emissions is 2% for liquids of boiling point 20 – 60 °C at 1 atmosphere, 1% for liquids of boiling point 60 – 120 °C at 1 atmosphere and 0.5% for gases [73]. The source of volatile organic compounds is decomposition of bloodmeal (a solid powder) and fugitive emissions are assumed therefore assumed to be 0.5% of the mass of bloodmeal used. Emissions are assumed to be volatile organic compounds. A global warming potential of 3.4 kgCO₂e/kgVOCs was used [9]. This gives a fugitive contribution to greenhouse gas emissions of 0.0087 kgCO₂e/kg polymer.

5.3.4.2 Emissions to water

The amount of wastewater (mostly washwater) produced by the proposed commercial plant is small enough to be treated by the municipal waste water treatment system. Approximately 200 - 500 litres of wastewater will be generated per washdown [106]. Washdowns will not be required everyday, and therefore the amount of water needing to be treated per kg NTP is small. Energy required for treatment of this wastewater is therefore assumed to be several orders of magnitude less than that used by the Novatein facility and has not been included.

5.3.4.3 Solid waste

The most significant source of solid waste is due to packaging of raw materials [106]. A small amount of purge material from cleaning the extruder will also be generated. Primary energy and emissions related to disposal of these have not been included in this analysis.

5.3.5 Conversion of energy inventory to impact categories

Primary energy and greenhouse gas emissions associated with the supply of process energy to the NTP facility are shown in Table 10. These have been calculated from energy inputs required by the plant (Table 9) combined with the primary energy and emissions factors for New Zealand fuel and electricity described earlier (Table 7).

Table 10: Gate to gate primary energy and energy related greenhouse gas emissions for manufacture of Novatein Thermoplastic Protein.

	Gas	Electricity (NZ mix)	Electricity (coal based)
Delivered energy (MJ/kg)	0.079	1.073	1.073
Non-renewable primary energy (MJ/kg)	×1.13= 0.090	×1.00= 1.07	×2.77= 2.97
Renewable primary energy (MJ/kg)	×0.00= 0.000	×1.36= 1.46	×0.00= 0.00
Total primary energy (MJ/kg)	×1.13= 0.090	×2.36= 2.53	×2.77= 2.97
Greenhouse gas emissions (kgCO ₂ e/kg)	×0.06096= 0.005	×0.06597= 0.071	×0.2712= 0.291

5.4 Production and delivery of non-bloodmeal material inputs

5.4.1 Water

Water is the second largest material input for the process. The plant is anticipated to be in Taranaki, a region of New Zealand with high rainfall. As such, except in the rare case of drought, water is abundant in the regional scope. Water is considered a raw material from the earth and does not need manufacturing within

the life cycle assessment boundaries. Regardless, energy is still used in pumping water, whether it be from a reticulated supply, from a stream or from a bore. Energy and greenhouse gas emissions for the supply of water from a variety of data sources are compared in Table 11.

Table 11: Primary energy and greenhouse gas emissions for the supply of water from a variety of data sources.

Source	Non-renewable primary energy (MJ/kg)	Greenhouse gas emissions (kgCO ₂ e/kg)
New Zealand reticulated [63]	0.003	-
Process water for production of PHA[23]	0.0038	0.0002
Cooling water for production of PHA [23]	0.0016	0.0001
California recycling [107]	0.017	0.0010
California imported [107]	0.018	0.0011
California desalinated [107]	0.043	0.0025

Primary energy for the delivery of reticulated water has previously been estimated as 0.003 MJ/kg [63]. The same data source used a coefficient for New Zealand electricity of 1.53 MJ_{primary}/MJ_{delivered} [63]. It was assumed that primary energy associated with water is from electricity for pumping and purification. The electricity consumption per kg of water was therefore calculated as 0.001961 MJ/kg. This was combined with the coefficients for primary energy and emissions of New Zealand electricity to calculate the data shown in Table 12 for the supply of water [68].

Table 12: Primary energy and greenhouse gas emissions for supply of New Zealand water for the production of NTP.

	Impact/ kg water	Impact/kg NTP
Non-renewable primary energy (MJ/kg)	0.00196	0.00060
Renewable primary energy (MJ/kg)	0.00267	0.00082
Total primary energy (MJ/kg)	0.00463	0.00142
Greenhouse gas emissions (kgCO ₂ e/kg)	0.000129	0.000039

5.4.2 Urea

Urea is an important industrial chemical with an important role in modern agricultural as a nitrogen source in fertiliser. Other uses include the manufacture

of resins, glues, solvents, some medicines and agricultural animal feed supplement [16].

Urea is a protein denaturant and is used in bio-based polymer materials made from proteins to increase chain mobility and increase the temperature gap between denaturing and degradation of the polypeptide chains.

5.4.2.1 Manufacture overview

Urea is manufactured by the direct reaction between ammonia and carbon dioxide to form ammonium carbamate, ($\text{NH}_2\text{COONH}_4$) which is simultaneously dehydrated at elevated temperature and pressure forming urea [16].

It is beyond the scope of this thesis to provide a full review of international ammonia production and the various technologies, feedstocks and varieties in emissions involved. Of particular relevance for NTP are the energy requirements and emissions associated with New Zealand urea supply. In New Zealand, there is only one plant producing urea, operated by a wholly owned subsidiary of Ballance Ag Nutrients [108]. Located in Kapuni, Taranaki, this plant is a combined ammonia/urea plant, manufacturing the ammonia and carbon dioxide required for urea production from natural gas and air.

Additional urea is imported into New Zealand to meet demand. The location of the NTP facility proposed in the commercial feasibility study was chosen for proximity to both the bloodmeal supply and urea supply from Ballance. As such, it is assumed the urea consumed in the production of Novatein Thermoplastic Protein is manufactured at the Kapuni site, rather than imported.

5.4.2.2 Primary energy and emissions to air

Primary energy use and emissions for New Zealand urea have previously been estimated to be 30 MJ/kg urea and 1.5 kgCO₂e/kg urea respectively [59]. These estimates were based on a review of reported international energy requirements for urea combined with information on the annual production and gas usage of the Kapuni site. It is assumed that these figures represent total non-renewable primary energy use and total greenhouse gas emissions in kgCO₂e. These values also include an allowance for capital and indirect inputs.

When urea is used as fertiliser some nitrogen is oxidised and emitted as N₂O rather than being absorbed by soil and biological systems. This represents an additional contribution to greenhouse gas emissions that is sometimes included with data on urea. It is assumed that the above figures did not include this contribution and are suitable for the cradle to gate analysis of NTP, where the urea is not used as a fertiliser.

Approximately half the natural gas used in producing ammonia and urea at Kapuni is used as fuel, with the remainder being incorporated into the molecular structure of the products [108]. The “feedstock” energy therefore can be estimated to be approximately half of the primary energy involved, i.e. 15 MJ/ kg urea. The impact results for urea used in the analysis of Novatein Thermoplastic Protein are shown in Table 13.

Table 13: Non-renewable primary energy and greenhouse gas emissions for the supply of urea.

	Impact/kg urea	Impact/kg NTP
Non-renewable feedstock energy (MJ/kg)	15	0.76
Non-renewable process energy (MJ/kg)	15	0.76
Total non-renewable energy (MJ/kg)	30	1.53
Greenhouse gas emissions (kgCO ₂ e/kg)	1.5	0.076

5.4.3 Sodium dodecyl sulphate (SDS)

Sodium dodecyl sulphate is an anionic surfactant. It has a charged end, with a long non-polar tail. It is used to reduce hydrophobic interactions between protein chains.

Non-renewable energy use and greenhouse gas emissions for sodium dodecyl sulphate have previously been estimated to be of 28.2 MJ/kg and -0.21kgCO₂e/kg [23]. This was done for the cradle to gate production of sodium dodecyl sulphate, included a life cycle assessments for polyhydroxyalkanoates [23]. In that scenario, it was assumed that it would be manufactured from palm oil, and that the carbon dioxide removed from the atmosphere when growing oil palms can be regarded as greenhouse gas emissions credit.

A more detailed analysis considered anionic alcohol sulphates manufactured from a variety of feedstocks, including oil, plant and animal sources. In that study, the cradle to gate non-renewable primary energy ranged between 48 and 79 MJ/kg [109].

Despite claims of sustainability, palm oil is not without controversy. Palm plantations have been blamed for deforestation of rainforest leading to loss of chimpanzee habitats. However, the amount of sodium dodecyl sulphate used in NTP is small (less than 2% by mass) and the associated contributions to deforestation of rainforest per kg of blood plastic are not likely to be significant. The impact results used for sodium dodecyl sulphate in the analysis of NTP, based on the PHA study, are shown in Table 14.

Table 14: Non-renewable energy use and net greenhouse gas emissions for sodium dodecyl sulphate.

	Impact/kg SDS	Impact/kg NTP
Non-renewable feedstock energy (MJ/kg)	0	0.0
Non-renewable process energy (MJ/kg)	28.2	0.431
Total non-renewable energy (MJ/kg)	28.2	0.431
Greenhouse gas emissions (kgCO ₂ e/kg)	-0.21	-0.0032

5.4.4 Sodium sulphite

Sodium sulphite is a reducing agent. Its role in protein based thermoplastic is to bind preferentially with sulphur containing cystein residues, preventing and breaking disulphide bridges between these.

5.4.4.1 Manufacture overview

The process for manufacturing sodium sulphite is abbreviated in Figure 10.

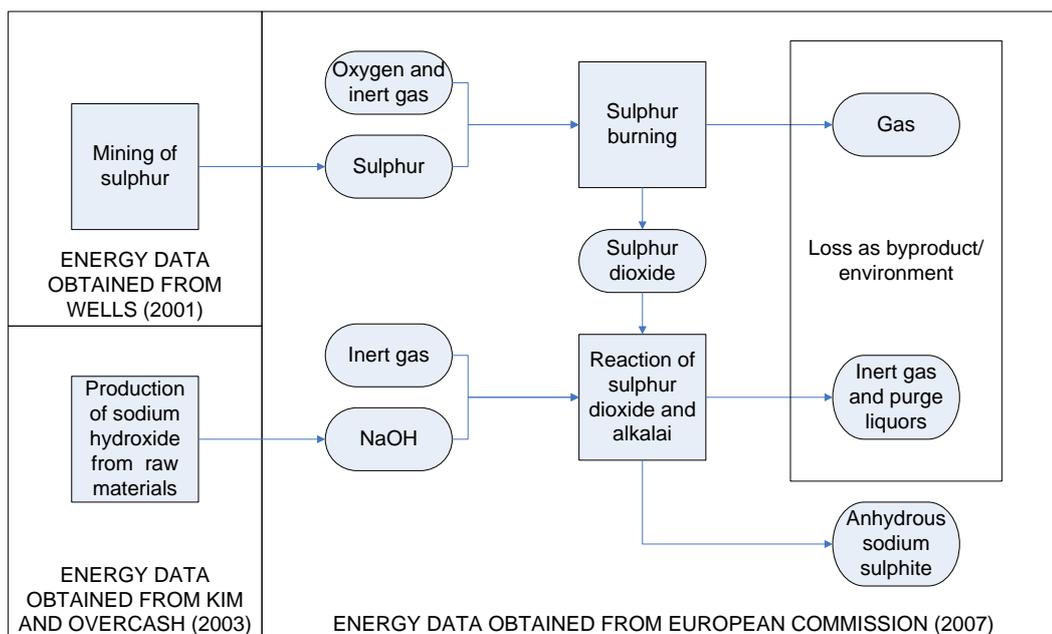


Figure 10: Manufacture of sodium sulphite [59, 110, 111].

Raw materials required for the production of 1000 kg sulphur dioxide are 501 kg sulphur and 3042 kg oxygen and inert gas, of which 2543 kg of gas is a by-product or loss to the environment [111]. Raw materials for the production of 1000kg anhydrous sodium sulphite are 616 kg sulphur dioxide, 542 kg sodium hydroxide and 3542 kg inert gas, with 3700 kg of gas and purge liquors as a by-product or loss to the environment [111].

5.4.4.2 Energy input

Combustion of sulphur is exothermic. 1 – 1.2 kg steam and 0.02 – 0.04 MJ electricity can be recovered per kilogram of sulphur dioxide produced [111]. Manufacture of anhydrous sulphites from sulphur dioxide, requires 2 – 4 kg of steam and 0.1 – 0.2 MJ electricity respectively [111].

The delivered energy content of steam of unknown pressure produced as a co-product is assumed to be 2.75 MJ/kg, consistent with the 2005 APME methodology for eco-profiles of the European plastics industry [51]. This figure was combined with the above energy requirements to estimate how much process energy, additional to that supplied by the combustion of sulphur, is needed to produce sodium sulphite, as shown in Table 15. The low end of the range has been assumed for the energy recoverable from combustion of sulphur and the high

end of the range has been assumed for the step producing sodium sulphite, representing a worst case.

Table 15: Delivered process energy requirements for manufacturing 1kg anhydrous sodium sulphite.

	Electricity MJ/kg	kg/kg	Steam MJ/kg
Required to produce sodium sulphite from sulphur dioxide	0.20	4.0	11
Less that recoverable from the production of sulphur dioxide ⁴	0.012	0.74	2.03
Additional process energy required	0.188	3.26	8.97

Additionally, energy is required for mining sulphur, and for production of sodium hydroxide used in the process. Energy use and emissions for mining of sulphur for use in New Zealand fertilisers are estimated to be 5 MJ/kg sulphur and 0.3 kgCO₂e/kg sulphur respectively [59]. In the absence of detailed information of sulphur sourcing for the production of sodium sulphite, these values have been assumed.

Like coal and petroleum, sulphur can be combusted as a non-renewable fuel. The energy content available from the combustion of sulphur is used in the process to make sodium sulphite. As such, no non-renewable “feedstock energy” is assumed for sodium sulphite used in making Novatein Thermoplastic Protein.

Additional energy is also required for the production of the sodium hydroxide, required for the reaction with sulphur dioxide. Delivered energy required to produce 1kg sodium hydroxide from raw materials was estimated as 3.16 MJ electricity and 0.38 MJ_{delivered} steam [110].

Non-renewable primary energy use and greenhouse gas emissions assumed for steam of unknown origin were 3.35 MJ/kg and 0.25 kgCO₂e/kg respectively [23].

⁴ 0.616 kg of sulphur dioxide is required per kilogram sodium sulphite. The energy per kilogram of sodium sulphite is therefore 0.616 multiplied by the energy recovered per kilogram of sulphur dioxide.

Using these values, along with the electricity factors for coal based generation discussed earlier (Table 7), non-renewable primary energy and greenhouse gas emissions for the above sub-processes in the production of sodium sulphite were calculated and are shown in Table 16.

Table 16: Non-renewable energy use and greenhouse gas emissions for processes in the production of 1 kg sodium sulphite.

	Non-renewable primary energy MJ/kg	Greenhouse gas emissions (kgCO ₂ e/kg)
Sulphur mining	1.54	0.093
Sodium hydroxide production	5.00	0.48
Sodium sulphite manufacture via sulphur dioxide	11.86	0.897
Total	18.39	1.47

5.4.4.3 Emissions to air

The release of sulphur dioxide to air is the most significant emission from manufacturing sulphite chemical products, followed to a lesser extent by particulate matter from handling dry materials [111]. Neither of these are direct contributors to global warming, so are not greenhouse gas emissions. As such, the relevant contribution to greenhouse gases is assumed to be due to production and delivery of energy required in additional process energy, as estimated with the primary energy data above.

The total impacts used for sodium sulphite in the analysis of Novatein Thermoplastic Protein are shown in Table 17.

Table 17: Non-renewable energy use and net greenhouse gas emissions for sodium sulphite.

	Impact/kg sodium sulphite	Impact/kg NTP
Non-renewable feedstock energy (MJ/kg)	0	0.000
Non-renewable process energy (MJ/kg)	18.39	0.187
Total non-renewable energy (MJ/kg)	18.39	0.187
Greenhouse gas emissions (kgCO ₂ e/kg)	1.47	0.0150

Sodium sulphite can also be made as a by-product of sulphur scrubbing in boilers. This reduces the efficiency of the boiler, requiring more primary energy to be used to provide the same amount of delivered energy, but decreases acidification

by removing sulphur oxides from the emissions. Sourcing sodium sulphite manufactured in this way may be an environmentally friendly option, but no LCI data was obtained to confirm this.

5.4.5 Plasticizer

Triethylene glycol is one plasticizer that has been used in the laboratory production of some Novatein Thermoplastic Protein formations. It improves flexibility and reduces brittleness of the material.

Triethylene glycol, along with diethylene glycol is a co-product of the production of ethylene glycol, produced by hydration of ethylene oxide [16]. Ethylene oxide is produced from ethylene, an important intermediate in the production of many chemicals from crude oil.

5.4.5.1 Manufacture overview

Figure 11 shows the relevant process flow diagram adapted from literature for the production of ethylene glycols [112].

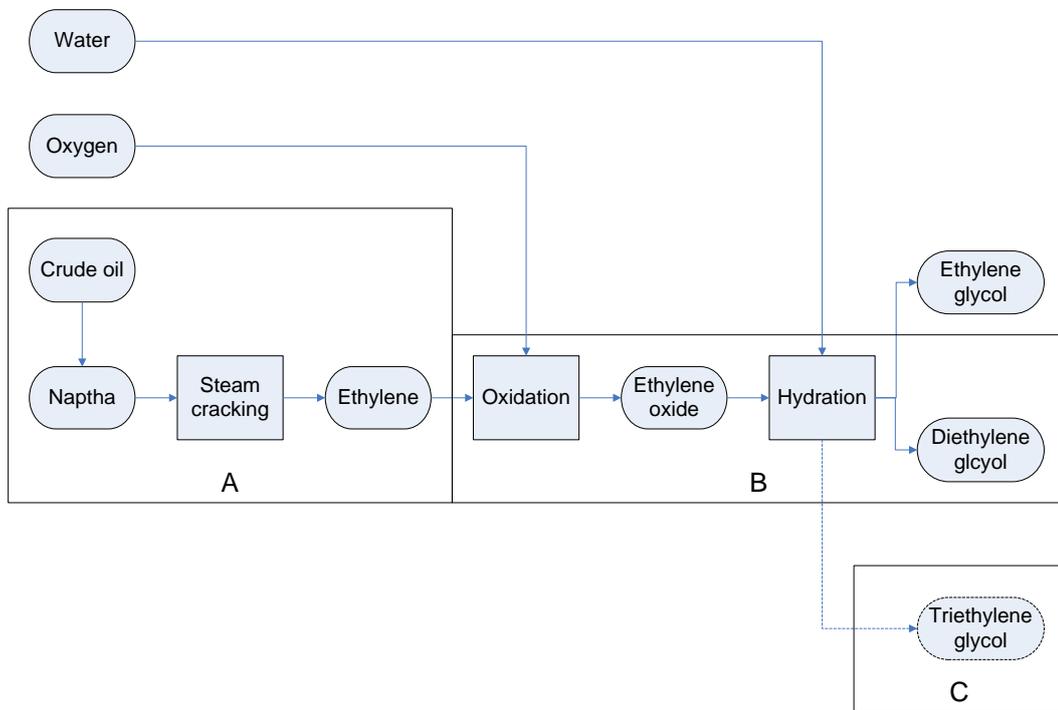


Figure 11: Production of ethylene glycols from crude oil [112].

Inventory data was obtained on production of the co-product ethylene glycol, which used 43.4 MJ/kg non-renewable primary energy and released greenhouse

gas emissions of 1.670 kgCO₂e/kg [113]. 26.5 MJ/kg represents the cumulative process energy, including upstream processes, whilst the remaining 16.9 MJ/kg represents primary energy embodied in the non-renewable feedstock.

The ratio by mass of different glycols produced by hydration of ethylene oxide can be controlled by the reaction conditions [16]. If it is assumed that impacts from hydration are the same for each unit of ethylene oxide that reacts, the primary energy for the overall process can be calculated for the higher glycols, based on the amount of ethylene oxide they contain. The amount of ethylene oxide that reacts to for each of the glycols is shown in Table 18.

Table 18: Amount of ethylene oxide reacted to form different ethylene glycols.

	Amount of ethylene oxide mol/mol	Molecular mass (g/mol)	Molecular mass of ethylene oxide incorporated (g/mol)	Amount of ethylene oxide (kg/kg)
Ethylene glycol	1	62.07	44.05	0.709683
Diethylene glycol	2	106.12	88.1	0.830192
Triethylene glycol	3	150.17	132.15	0.880003

Multiplying the non-renewable primary energy and greenhouse gas emissions by the mass of ethylene oxide required for each glycol, relative to that for ethylene glycol obtained the values shown in Table 19.

Table 19: Non-renewable primary energy use and greenhouse gas emissions for various glycols.

	Feedstock energy (MJ/kg)	Process energy (MJ/kg)	Total non-renewable primary energy (MJ/kg)	Greenhouse gas emissions (kgCO ₂ e/kg)
Ethylene glycol	16.9	26.5	43.4	1.67
Diethylene glycol	19.77	31.00	50.77	1.95
Triethylene glycol	20.96	32.86	53.82	2.07

5.4.6 Alternative data for plasticizer

Total primary energy was obtained for the production of ethylene (Box A in Figure 11) estimated at 67.570 MJ/kg in a paper describing methodology for

estimating the life cycle inventory of chemicals, of which 99.7% is from non-renewable sources [114]. A later paper using that methodology estimated that the primary energy per kg of ethylene oxide was 2.4 MJ less than that per kg ethylene after accounting for process energy and the additional mass of oxygen [112]. Likewise, the primary energy per kg of diethylene glycol was estimated to be 8.2 MJ less than that per kg of ethylene oxide, after accounting for process energy and the mass of water reacted [112].

The total primary energy can therefore be determined for diethylene glycol and its intermediates as shown in Table 20.

Table 20: Primary energy to produce ethylene oxide and diethylene glycol (alternative data source) [112, 114].

	Primary energy (MJ/kg)
Ethylene	67.57
Ethylene oxide (65.57 minus 2.4)	65.17
Diethylene glycol (65.14 minus 8.2)	56.97

Assuming the same percentage of renewable energy as for ethylene, this results in 56.8 MJ/kg non-renewable primary energy for production of diethylene glycol. This is 12% higher than that calculated above (Table 19).

5.4.7 Inventory results for TEG used in this assessment

The inventory results used for triethylene glycol is shown in Table 21. An increase of 12% on these results is considered in the sensitivity analysis included in the next chapter.

Table 21: Non-renewable energy use and greenhouse gas emissions used for triethylene glycol, showing split between feedstock and process energy.

	Impact/kg TEG	Impact/kg NTP
Non-renewable feedstock energy (MJ/kg)	20.96	2.14
Non-renewable process energy (MJ/kg)	32.86	3.35
Total non-renewable energy (MJ/kg)	53.82	5.48
Greenhouse gas emissions (kgCO ₂ e/kg)	2.07	0.21

5.4.8 Titanium dioxide

Information on the production of titanium dioxide was obtained from Reck and Richards (1999) who presented a life cycle assessment completed using the Boustead database and software [115]. That work compared a number of different methods of producing titanium dioxide, and based on the worst case, a value of 105 MJ/ kg TiO₂ non-renewable primary energy was assumed.

5.4.8.1 Emissions to air

Reck and Richards (1999) did not report emissions data for greenhouse gases, instead focussing on the release of sulphur dioxide, a contributor to the life cycle impact category of acidification. However, it is stated that gaseous emissions are dominated by the combustion of fossil fuels for onsite energy and for electricity generation [115].

A combined greenhouse gas emissions factor of 0.9397 kgCO₂e/MJ_{primary} for energy supplied by sub-bituminous coal was obtained from Barber (2009) [68]. Although this factor is for New Zealand coal, in the absence of detail about the fossil fuels used in manufacturing titanium dioxide, it has been used to assume a worst case for unspecified fossil energy. This results in greenhouse gas emissions of 9.9 kgCO₂e/kg TiO₂. It is also assumed that there is no “feedstock” energy associated with the production of Titanium oxide. This is reasonable as it is not an organic molecule manufactured from crude oil. The impact category results are shown in Table 22.

Whilst these inventory figures represent a cruder approximation than for some other data contained in this chapter, in this case it can be justified, as titanium dioxide is less than 1% of the NTP by mass.

Table 22: Non-renewable energy use and greenhouse gas emissions for the production of titanium oxide.

	Impact/kg titanium dioxide	Impact/kg NTP
Non-renewable feedstock energy (MJ/kg)	0	0.00
Non-renewable process energy (MJ/kg)	105	0.70
Total non-renewable energy (MJ/kg)	105	0.70
Greenhouse gas emissions (kgCO ₂ e/kg)	9.9	0.065

5.5 Blood drying into bloodmeal

5.5.1 Manufacture overview

Animals in New Zealand are slaughtered by stunning and then exsanguination (bleeding out). Raw blood has a high biological and chemical oxygen demand and therefore should not be released into the environment. Instead it is collected and processed into products that can be sold [34].

Some animal blood is used in applications for human consumption, but needs to be collected hygienically if this is to be the case. In practice, a large volume of blood is not collected hygienically and is used to make bloodmeal [34].

There are three common methods to produce bloodmeal and these are shown in Figure 12. Each method produces a powder with different solubility and different degrees of damage to the protein [33]. The first process, drying by direct addition of heat to whole blood is energy intensive [33]. The second process, coagulation and mechanical separation followed by drying is the conventional process [116]. It can be performed either in batches or in a continuous fashion.

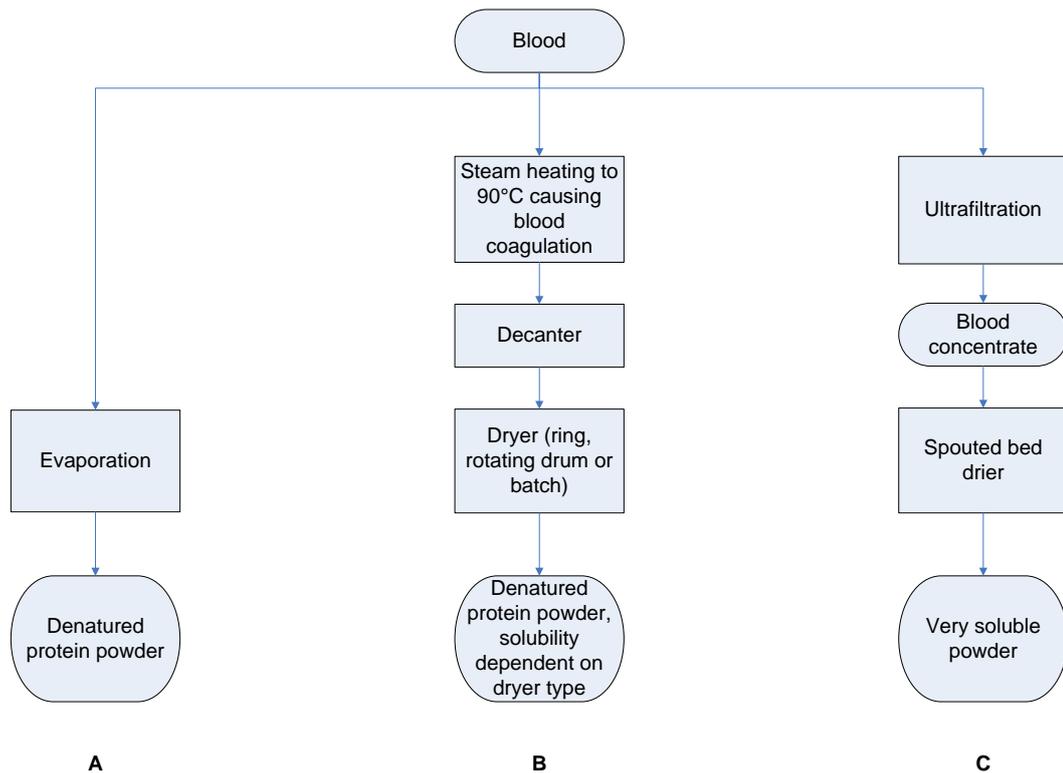


Figure 12: Common methods of drying blood [33].

Poor coagulation procedures or excess dilution with washwater when collecting the blood can reduce the yield of recoverable protein when manufacturing bloodmeal [116]. Aging of the blood, even overnight, can make coagulation easier and increase yield but also contributes to foul odours which must be managed [116].

The bloodmeal being sourced for production of NTP is produced from bovine blood using the second method (B) in a continuous process. Process information used in this analysis is based on a site visit to Taranaki By-Products (TBP) in September 2009 with data from the plant manager supplemented with values from literature for missing information [34, 117, 118]. The TBP site in Hawera also renders other inedible materials from meat processing in addition to producing bloodmeal.

The blood is kept separate from other inedible portions of the animal and processed on separate equipment, however, these facilities are located on the same site and powered by the same boilers and electricity supply as the rest of the plant.

Figure 13 shows the process used at the TBP site in more detail, with the solid lines representing material flows and the dashed lines representing energy inputs. Energy data provided was for the whole plant, rather than just the blood drying portion.

In addition to emissions from energy supply, volatile organic compounds (mostly ammonia) are released as water is evaporated. These are extracted and passed through a series of biofilters to mitigate odour effects. Additionally, waste water treatment ponds and irrigation of treated effluent are a potential source of emissions.

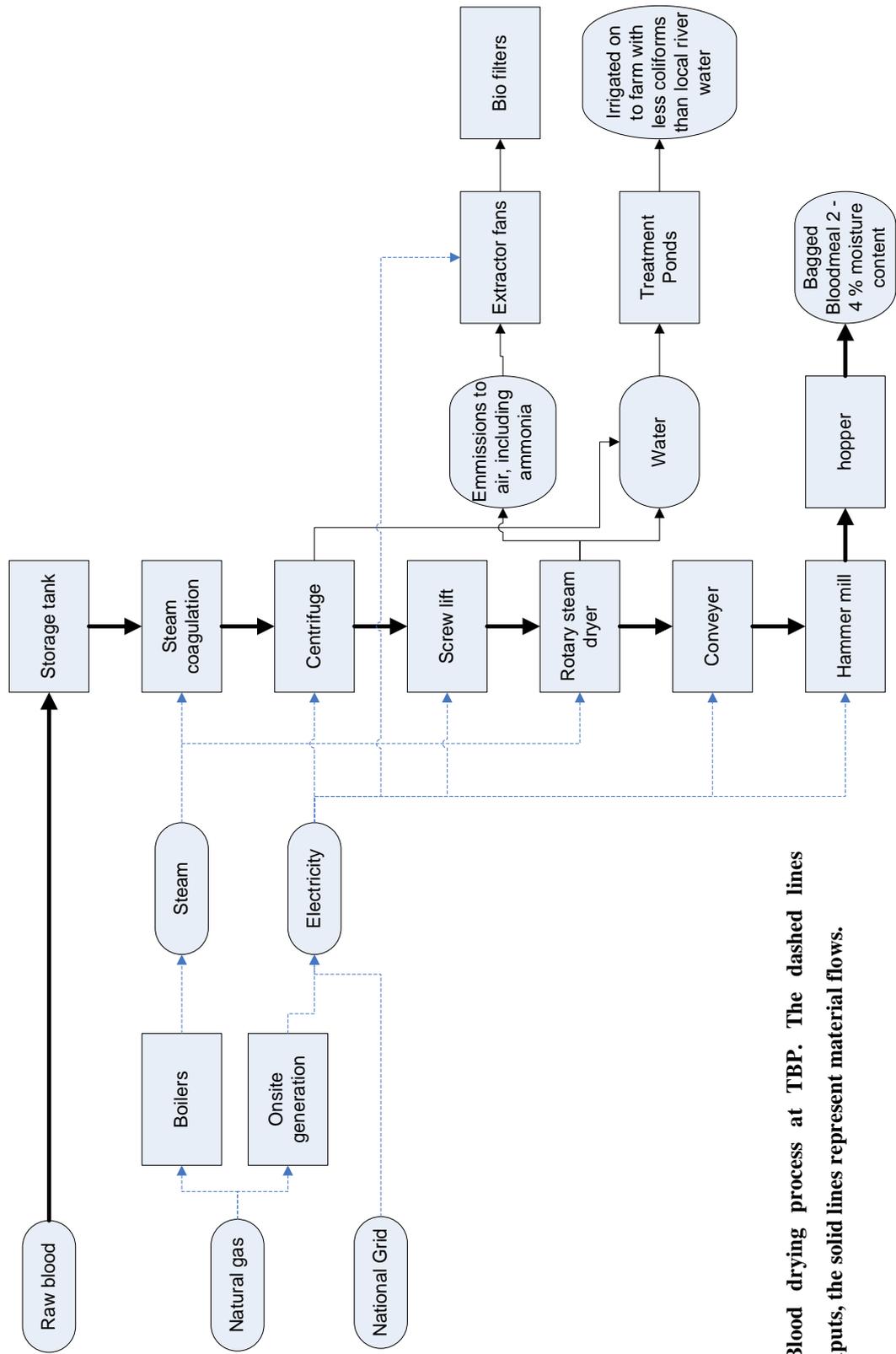


Figure 13: The Blood drying process at TBP. The dashed lines represent energy inputs, the solid lines represent material flows.

5.5.1.1 Mass and Energy Data

The plant operates a continuous process, but is shut down daily for about an hour maintenance. About 6 tonnes of raw material is processed hourly with a yield of 600 kg bloodmeal, at 2-4 wt% moisture.

Raw blood (plus washwater) is coagulated with steam and then decanted before being dried in a rotary drier. Although the solids content of raw blood is 19 wt%, in practice it is diluted with washwater etc, and has a solids concentration between 10 and 15% [118].

A mass balance for undiluted raw blood is shown in Figure 14 for an abbreviated block flow diagram adapted from Filstrup [34].

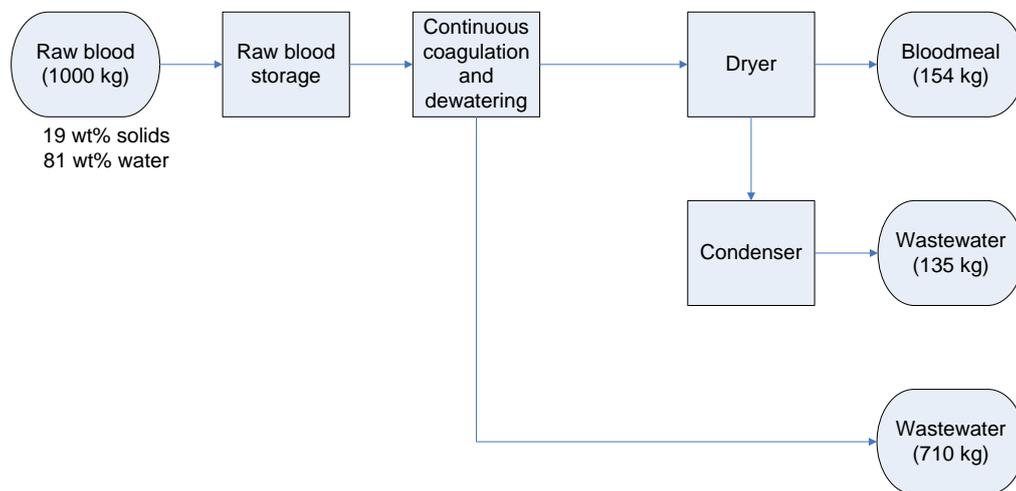


Figure 14: Mass Balance for drying of undiluted raw blood. Adapted from Filstrup [34].

Typically, a 15% yield of bloodmeal can be expected from undiluted raw blood [118]. At TBP, a 10% yield was reported using diluted blood, collected over large parts of the North Island of New Zealand. A mass balance of the bloodmeal production process can be completed assuming the following values:

- 40 wt% solids after coagulation and dewatering [34].
- 92% of the solids are coaguable
- Bloodmeal contains 96 wt% solids [117].

It can be shown that:

- Diluted blood entering the coagulator contains 12.2 wt% solids.
- Waste water from the coagulation and dewatering contains 1.4 wt% solids [116].
- Waste water from the condenser contains 8.9 wt% solids

This new mass balance, representing the data for TBP is shown in Figure 15.

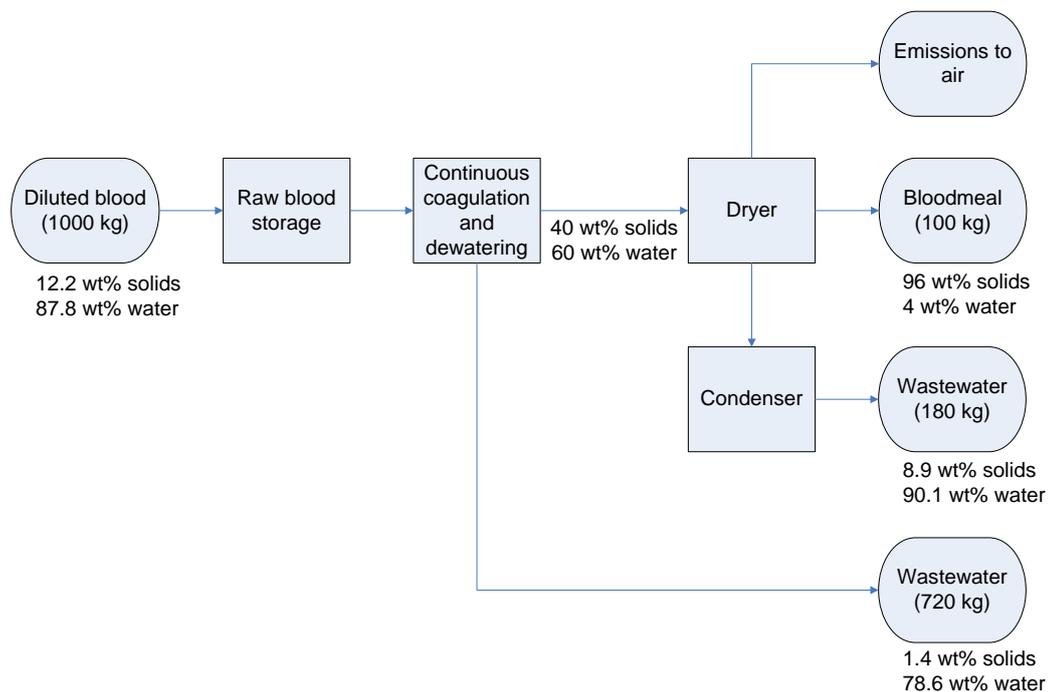


Figure 15: Mass balance for drying of diluted blood at TBP.

5.5.2 LCI (Gate to Gate)

The TBP plant under consideration utilises 2 GJ gas and 90 kWh electricity from the national grid per tonne of raw material entering the plant [117]. Raw material includes both diluted blood and other inedible portions of animals which are rendered on the same site. The yield of bloodmeal is 10 wt% of the raw material processed. The delivered energy requirements for production of bloodmeal based on this yield are shown in Table 23, along with the primary energy and greenhouse gas emissions associated with the production of process energy. These have been calculated using the factors discussed in section 5.2.3.

Table 23: Gate to gate primary energy and energy related greenhouse gas emissions for manufacture of bloodmeal.

	Gas	Electricity (NZ mix)	Electricity (coal based)
Delivered energy (MJ/kg)	20.00	3.24	3.24
Non-renewable primary energy (MJ/kg)	22.60	3.23	8.98
Renewable primary energy (MJ/kg)	0.00	4.41	0.00
Total primary energy (MJ/kg)	22.60	7.65	8.98
Greenhouse gas emissions (kgCO ₂ e/kg)	1.219	0.214	0.879

5.5.2.1 Emissions to air

Emissions to air associated with energy use in producing bloodmeal were included in Table 23. However, there are also emissions of volatiles and particulate matter from the blood drying itself.

The United States Environmental Protection Agency has listed estimated emission factors for filterable PM₁₀, condensable particulate matter, ammonia and hydrogen sulphide from blood drying in natural gas direct fired driers [119]. These are shown in Table 24 on the basis of kg emitted/ kg bloodmeal produced.

Table 24: Direct emissions from blood drying [119].

Pollutant	Emission (kg emitted/kg bloodmeal)
PM ₁₀	0.00038
Condensable PM	0.00023
Ammonia	0.0003
Hydrogen Sulphide	0.00004

Different drying methods can be expected to have different emissions profiles, but it can be assumed that the order of magnitude will be similar, and can be used to check for the significance. In the visited plant, air from the blood drying room is passed through a series of biofilters to remove pollutants, especially ammonia [117]. It is assumed that full oxidation of ammonia to N₂O occurs during this process, and represents the contribution to greenhouse gas emissions. Based on the molecular mass of ammonia and nitrous oxide, an emission of 0.00039 kgN₂O/kg bloodmeal is assumed. Nitrous oxide has a global warming potential of 310 kgCO₂e/kgN₂O on a 100 year time span [9]. This represents an additional

0.12 kg CO₂e/(kg bloodmeal). This is an order of magnitude less than the contribution from process energy.

Water removed during blood is treated by a series of oxidation ponds. Treated water is irrigated onto the surrounding farmland with less coliforms than the background level found in local watercourses. Direct energy requirements for irrigation is assumed to be included in the total energy requirement for the TBP facility. The oxidation ponds are assumed to be operated aerobically, resulting in mostly CO₂ emissions. The CO₂ is also assumed to be of recent biological origin, and therefore negated by an equivalent uptake by biomass in the processes upstream of its release. Emission of nitrogen containing species when the effluent is subsequently irrigated is assumed to be equivalent to that of other nitrogenous fertiliser use, and so is attributed to farming, rather than waste treatment and is not included here.

5.5.2.2 Comparison with international blood drying data sources

In order to establish the international relevance of the data collected for the TBP facility, the process was compared to data sourced from the Danish Life Cycle Inventory [120]. In this database, the energy requirements of plants producing bone, blood and meat meals as 82 kWh electricity and 1.9 GJ fuel per tonne of abattoir waste [120].

The European Commission's best-practice-document for the Animal By-Products Industry estimated requirements to be 120 kWh electricity and 2.4 GJ of fuel oil⁵ for an unspecified blood drying process [121]. In the same report, average energy requirements of four general rendering plants were reported to be 83 kWh electricity and 2.5 GJ fuel oil. The also considered different rendering technologies and found the energy requirements ranged between 68 – 91 kWh electricity and 1.8 – 3.6 GJ fuel oil.

This indicates that the combined energy use at the TBP plant energy usage is in a similar range to international rendering and blood drying facilities.

⁵ Fuel oil can refer to a number of different fuels derived from crude oil that can be burned for heat. The European Commission report uses a value of 40 MJ usable heat/kg fuel oil.

The relative ratio of blood to other inedibles requiring rendering is assumed to remain constant. Table 25 summarises the non-renewable energy use and emissions for blood drying used in this analysis.

Table 25: Summary of non-renewable energy use and greenhouse gas emissions in blood drying.

	Impact/kg bloodmeal	Impact/kg NTP
Non-renewable primary energy (gas) (MJ/kg)	22.60	11.51
Non-renewable primary energy (electricity) (MJ/kg)	3.23	1.65
Total non-renewable primary energy (MJ/kg)	25.83	13.16
Energy greenhouse gas emissions (kgCO ₂ e/kg)	1.43	0.73
Direct greenhouse gas emissions (kgCO ₂ e/kg)	0.12	0.06
Total greenhouse gas emissions (kgCO₂e/kg)	1.55	0.79

5.6 Farming and meat processing

Primary energy and greenhouse gas emissions for farming and meat processing were obtained from a report to the Energy Efficiency and Conservation Authority (EECA) on biodiesel derived from New Zealand tallow [57]. That analysis included diesel and electricity use, agrichemicals, additional feed purchased and energy embodied in capital items. Data for farming in the report was calculated based on the Agriculture Research Group on Sustainability (ARGOS) database for the 2003/2004 season and data on meat processing was based on a Meat Industry Research Institute of New Zealand (MIRINZ) report for the 1994/1995 season.

The unallocated impacts of farming and of meat processing with regard to primary energy use and greenhouse gas emissions are shown in Table 26 and Table 27 respectively. They are based on a carcass weight of 275kg and a live weight of 500 kg. It is assumed that all the primary energy used is non-renewable, however, a small portion is for the production of electricity, some of which may be renewable.

Assuming that collection of blood requires the same amount of primary energy as all other parts of a live animal, the primary energy of farming and meat processing per kg of bloodmeal can be calculated as shown in Table 26 and Table 27. This

assumption constitutes a form of simple mass allocation for dividing a multifunctional process. The implications of this form of allocation, problems with it, and the results of other allocation techniques are discussed in the next chapter.

Table 26: Primary energy and greenhouse gas emissions for farming of cattle [57].

	Non-renewable primary energy (MJ/kg)	Greenhouse gas emissions (kg CO ₂ e/kg)
Unallocated impact per kg live animal	5.4	4.0
Unallocated impact per kg carcass	9.9	7.2
Unallocated impact per kg bloodmeal ⁶	1210	880.0
Allocated impact per kg bloodmeal, using mass fraction of blood as allocation factor	36.3	26.4
Per kg Novatein Thermoplastic Protein (simple mass allocation)	18.5	13.4

Table 27: Primary energy and greenhouse gas emissions from meat processing [57].

	Non-renewable primary energy (MJ/kg)	Greenhouse gas emissions (kg CO ₂ e/kg)
Unallocated impact per kg live animal	1.6	0.06
Unallocated impact per kg carcass	2.9	0.12
Unallocated impact per kg bloodmeal ⁶	354.4	14.08
Allocated impact per kg bloodmeal, using mass fraction of blood as allocation factor	10.63	0.42
Per kg Novatein Thermoplastic Protein (simple mass allocation)	5.42	0.22

5.6.1 Carbon content of Novatein Thermoplastic Protein

Emission and removal of carbon dioxide for systems using biomass should be explicitly accounted for, for each stage a life cycle [122]. The carbon contained in bloodmeal is biogenic in origin, having been photosynthesised by feed crops and then eaten by cattle. In a full cradle to grave system this carbon would likely be

⁶ This represents the total impact of enough live animal to produce 1 kg bloodmeal, including all other products and by-products also produced at the same time. It is based on 3 wt% blood from live weight, and 15 wt% bloodmeal recoverable from blood and represents 222 kg live animal.

returned to the atmosphere via decomposition processes. On a cradle to gate basis however, some consideration must be given to the carbon being temporarily stored in the bio-based polymer at the end of the system boundary.

Carbon uptake during production of biomass for biobased polymers can be considered as separate process with negative CO₂ emissions [13]. The uptake of carbon into biomass was not included in the emissions for farming reported in Barber et al (2007) [57] and is calculated here.

Bloodmeal is predominantly protein which is 55% carbon by mass, assumed to be entirely from recent photosynthesis. 1 kg of bloodmeal is therefore assumed to contain 0.55 kg of biogenic carbon, which is the carbon content of 2.0 kg CO₂ from the atmosphere. Table 28 shows the resultant biogenic carbon content and associated removals of atmospheric carbon dioxide based on the mass fraction of bloodmeal Novatein Thermoplastic Protein.

Table 28: Biogenic carbon content and assumed CO₂ uptake of bloodmeal and Novatein Thermoplastic Protein.

	Bloodmeal	Novatein Thermoplastic Protein
Biogenic carbon content	55%	28%
Carbon dioxide assumed removed from the atmosphere	2.02 kgCO ₂ e/(kg bloodmeal)	1.03 kgCO ₂ e/kg NTP

5.7 Transport

The unit processes included in the scope of this study do not occur at the same geographical location. As such, transport of intermediates needs to be considered in the assessment. Transport steps included in the analysis are shown in Table 29.

5.7.1 Assumed distances

TBP is located 10.4 km, by road, from Ballance Agri Nutrients and 74.9 km from Port Taranaki. The proposed Novatein Thermoplastic Protein facility is assumed to be within 15 km of both the bloodmeal facility and the Kapuni urea factory and 75 km from Port Taranaki.

The average distance from farm to abattoir was assumed to be 100km, consistent with data on farming and meat processing [57]. Additionally, TBP collect blood

from more than one abattoir, and the same average distance was assumed for transport from each location.

100 km was also assumed for the distance travelled between the factories where imported ingredients are made and the port they are shipped from.

Table 29: Transport assumed in the production of Novatein Thermoplastic Protein.

Resource transported	Mass transported kg/kg NTP	Distance by truck at origin (km)	Distance by truck to Novatein (km)	Distance by Ship (km)	Transport by Truck (kgkm/kg NTP)	Transport by ship (kgkm/kg NTP)
Blood ⁷	3.396	n/a	100	n/a	339.62	n/a
Diluted blood	5.094	n/a	100	n/a	509.42	n/a
Bloodmeal	0.509	n/a	15	n/a	7.64	n/a
Subtotal: Transport in supply of bloodmeal					856.68	0.00
Water	0.3057	n/a	n/a	n/a	n/a	n/a
Urea	0.0509		15	n/a	0.76	n/a
Sodium dodecyl sulphate	0.0153	100	75	20,000	2.67	305.65
Sodium sulphite	0.0102	100	75	20,000	1.78	203.77
Triethylene glycol	0.1019	100	75	20,000	17.83	2037.70
Titanium dioxide	0.0066	100	75	20,000	1.16	132.45
Subtotal: Transport in supply of non-bloodmeal additives					24.21	2679.57
Total transport in the production of NTP					880.89	2679.57

5.7.2 Conversion to impact categories

The non-renewable primary energy use assumed for transport is 0.001 MJ/kgkm for articulated trucks and 0.0002 MJ/kgkm for international bulk carriers [65]. Assuming in both cases that all of this primary energy is supplied by diesel, and using the coefficient of 0.0688 kgCO_{2e}/MJ_{primary} published by Agrilink, primary energy and greenhouse gas emissions can be calculated [68]. These are shown in Table 30.

⁷ This represents the mass of blood required to produce enough bloodmeal for NTP manufacture. It is moved, along with the rest of a live animal, from farm to abattoir.

Table 30: Contribution of transport to primary energy and greenhouse gas emissions of Novatein Thermoplastic Protein.

	Non-renewable primary energy (MJ/kg NTP)			Greenhouse gas emissions (kgCO ₂ e/kg NTP)		
	Transport of animals, blood and bloodmeal	Transport of non- bloodmeal additives	Total transport	Transport of animals, blood and bloodmeal	Transport of non- bloodmeal additives	Total transport
Truck	0.857	0.024	0.881	0.059	0.002	0.061
Ship	0.000	0.536	0.536	0.000	0.037	0.037
Total	0.857	0.560	1.417	0.059	0.039	0.097

5.8 Summary of entire cradle to gate system

Table 31 summarises the contribution of all processes considered to non-renewable primary energy and greenhouse gas emissions in the production of Novatein Thermoplastic Protein.

In the cradle to gate system described above, emissions from farming contribute 96% of the net greenhouse gas emissions. Also, emissions from farming are 13 times higher than the biogenic carbon credit of bloodmeal used to make Novatein Thermoplastic Protein.

Farming is the largest contributor to non-renewable primary energy demand, contributing 39%. The production of bloodmeal, including farming and meat processing, uses considerably more non-renewable energy than production of non-bloodmeal additives (37.93 MJ versus 8.9 MJ respectively). The gate to gate energy in the proposed Novatein facility is rather small by comparison contributing only 2% of the total for the cradle to gate system.

Although water is the second largest component of Novatein Thermoplastic Protein by mass, the energy involved in supplying water is very small compared to other non-bloodmeal additives. Changing from water to including petrochemical plasticizers could therefore significantly change its profile, as energy to produce alternative plasticizers will be increased.

Table 31: Initial life cycle impact assessment for production of 1 kg Novatein Thermoplastic Protein.

Unit process	Non-renewable energy use			Greenhouse gas emissions (kgCO ₂ eq)
	Feedstock (MJ)	Process (MJ)	Total (MJ)	
NTP processing				
Process energy	n/a	1.160	1.160	0.076
Direct emissions	n/a	n/a	n/a	0.0087
	n/a	1.160	1.160	0.084
Non-bloodmeal additives				
Water supply	0	0.0006	0.0006	0.00004
Urea manufacture	0.764	0.764	1.528	0.076
Sodium dodecyl sulphate	0	0.431	0.431	-0.003
Sodium sulphite manufacture	0	0.187	0.187	0.015
Triethylene glycol manufacture	2.135	3.348	5.483	0.211
Titanium dioxide manufacture	0	0.695	0.695	0.065
Transport of non-bloodmeal additives	n/a	0.560	0.560	0.039
	2.899	5.987	8.886	0.403
Production of bloodmeal				
Blood drying	0	13.16	13.16	0.79
Farming	0	18.49	18.49	13.45
Meat processing	0	5.42	5.42	0.22
Biogenic carbon content	n/a	n/a	n/a	-1.03
Transport of animals, blood and bloodmeal	n/a	0.86	0.86	0.059
	0.00	37.93	37.93	13.49
Total	2.90	45.07	47.97	13.97

It should be noted that the high contribution of farming to non-renewable primary energy use and greenhouse gas emissions in this summary is based on the assumption that impacts from a given live weight of animal are equally distributed across all parts of that animal. Such an assumption does not take into account the primary reason for raising beef cattle, nor does it account for some parts of an animal being waste.

The next chapter will explore the impact of alternative allocation scenarios on the impacts of producing Novatein Thermoplastic Protein, and discuss the limitations of this life cycle inventory before comparing with other bio-based polymers.

6 Discussion and limitations of inventory and impact assessment

6.1 Introduction

The final phase of life cycle assessment in accordance with ISO 14040 is life cycle interpretation [36]. This consists of identifying significant issues, evaluating them, and reporting them as conclusions [41]. Limitations of inventory analysis and impact assessment are also discussed.

Significant issues in the cradle to gate portion of the life cycle of Novatein Thermoplastic Protein are:

- The allocation method used for products of farming and meat processing.
- Generation of electricity.
- The formulation used, specifically the inclusion of plasticizers.

A sensitivity analysis was used to evaluate the significance of assumptions made when compiling the inventory for Novatein Thermoplastic Protein. Evaluation of data quality and a description of sources of uncertainty are also included in this chapter, before a comparison with other bio-based polymers.

6.2 Allocation issues

Allocation procedures vary widely in published life cycle assessments and no clear precedent exists for allocating impacts of farming and meat processing to a polymer made from bloodmeal or low value by-products.

The most significant issue in the cradle to gate profile for Novatein Thermoplastic Protein from the previous chapter is the proportionally large contribution of farming and meat processing to both impact categories considered. In particular, emissions from farming are excessively large compared with other biobased polymers identified in Chapter Three. The contribution was calculated using a mass based allocation of energy use and greenhouse gas emissions to produce the required bloodmeal for 1 kg polymer. Such an allocation method reflects a

physical relationship but that relationship does not necessarily correlate to the causes of environmental impacts.

Appropriate allocation of impacts from multi-function processes is one of the biggest challenges in life cycle assessment and one of the most talked about methodological issues [123]. Practitioners investigating comparable systems have used a variety of methods.

As discussed in chapter three, the standards on life cycle assessment include a stepwise procedure for allocation [39]:

- 1) Remove need for allocation using system expansion or subdivision of unit processes. If this is not practical then:
- 2) Allocate based on the causal relationships between products and environmental impacts. This is not always a simple physical quantity such as mass.
- 3) Allocate based on other relationships, for example economic value, that reflect the motivations behind performing activities that cause environmental impacts.

Avoiding allocation by subdivision is only possible when a system can be broken down into single function unit processes [124]. A separation, such as the division of one live animal into multiple products is inherently multifunctional. Therefore, in the case of bloodmeal used to produce Novatein Thermoplastic Protein, subdivision cannot be used to avoid allocation. Any impacts from single function sub-processes can be attributed entirely to their functions, leaving only the shared sub-processes needing allocation [124].

In practice, allocation by mass of co-products is common and easy to apply [113]. Some practitioners, however, suggest that simple mass partitioning should be avoided in as it can lead to absurd results [51]. Specifically, simple mass allocation does not take into consideration that the motivation for beef farming is production of meat, not a low value by-product such as bloodmeal. Mass allocation also requires a decision as to which masses should be used as a basis. This is complicated with the downstream separation of an output from one unit

process into wastes and products as is the case with the production of bloodmeal. If whole blood is considered as a product of farming and meat processing before separation, the mass used for allocation is a lot larger than if only the solids recoverable after separation are considered a product.

Economic allocation is sometimes used to allocate environmental impacts where an activity is motivated by production of a main product, such as meat, but other products are also produced, such as bloodmeal and other rendering products. However, one of the difficulties with economic allocation is the selection of an appropriate price for each product. New uses of a product may result in additional demand, thereby causing an increase in price. For example, protein recovery techniques, other than production of bloodmeal, exist for blood which result in higher value products [116]. Another shortcoming of economic analysis is that prices vary based on a large number of factors independent of the manufacturing process. Economic fluctuations are not constant between co-products either. For example, bloodmeal may drop in price at the same time as meat prices increase. The impacts attributed to products can therefore change without any change in the technology or process used [51].

Alternatively, mass allocation can be used for main products, with no allocation to low value by-products [113]. Under such procedure, emissions and process energy of farming and meat processing would be allocated entirely to the main products such as meat and not to bloodmeal. Such a procedure could be justified if the total impacts from a unit process are dependent solely on demand for the main products. That is, if the total amount of farming and meat processing is independent of demand for bloodmeal. The weakness of such an approach is that the results for the main product do not clearly distinguish between processes where a low value by-product is disposed of instead of used. Under such an allocation, the emissions or energy use of farming and meat processing allocated to meat would be identical whether bloodmeal was used or not⁸.

⁸ It should be noted that additional impact categories, such as biological oxygen demand, would not be the same, but these are not included in every assessment.

Another approach is to only allocate to by-products the impacts that would be associated with fulfilling their function by whatever process would be used to fulfil that function in the absence of the main product. For example, bloodmeal can be used as a fertiliser to deliver nitrogen to soil and could be attributed the energy and emissions required to deliver the same amount of nitrogen with a different fertiliser. Such a technique is a form of system expansion, and can be useful in consequential comparative LCAs for decision making. However, like economic allocation, such an allocation method depends on things outside of the technological coverage of the system being investigated. As such, it is not appropriate for an attributional LCA, such as an eco-profile of plastics [51].

6.2.1 Allocation within rendering and blood processing

One goal of this study is to estimate the greenhouse gas emissions and non-renewable energy for producing Novatein Thermoplastic Protein. This is an attributional approach to life cycle assessment and system expansion is therefore not appropriate [51]. Utilities such as steam generation and electricity demand, filtration of odourous air and waste water treatment are shared throughout the whole facility and therefore deemed multi-functional sub-processes. Elimination of the need for allocation via subdivision is therefore not possible [124]. Subdivision does, however, justify the consideration of blood drying and other rendering operations as separate unit processes, rather than allocating their impacts as part of waste treatment across all meat products. Such a division recognises that there are other waste treatment options for blood which do not produce bloodmeal.

Allocation of impacts from energy use for rendering and waste treatment cannot be avoided and are partitioned to reflect their underlying physical relationship. For the cases considered here, it is assumed that overall energy use of the rendering plant is dependent on the total mass of raw material entering the plant and independent of the ratio of blood to other rendering material. Mass can therefore be used as a physical relationship causing impacts related to rendering and blood drying energy. Direct emissions from blood drying have been calculated separately for that process alone.

Transport from the slaughterhouse to the render facility is also assumed to be dependent on the mass of diluted blood.

6.2.2 Allocation and biogenic carbon content

The removal of carbon dioxide from the atmosphere represented by the biogenic carbon content of bloodmeal used in manufacturing NTP can be considered as a separate unit process with negative CO₂ emissions [13].

The mass of carbon dioxide removed from the atmosphere within the system boundaries is assumed to be directly proportional to the mass of biogenic carbon contained within the biomass. Therefore, if allocation is not avoided by system expansion or process separation, allocation based on the mass of carbon is appropriate and consistent with the stepwise procedure in the LCA standards.

6.2.3 Allocation of impacts from farming and meat processing

From the perspective of bloodmeal, farming and meat processing are related unit processes. The product of farming is a whole live animal, which is then slaughtered and divided into multiple outputs in meat processing. The allocation of the two processes are therefore related in the absence of detailed process data needed to subdivide meat processing. Transport of live animals between the farm and the slaughterhouse is assumed to be allocated in the same manner as farming and meat processing. A number of different approaches have been used in LCAs of systems that could serve as an exemplar for the production of a bio-based polymer from bloodmeal.

- Systems using animal by-products:
 - Economic allocation was used to divide impacts from farming and meat processing for the production of biodiesel from New Zealand tallow [57].
 - A life cycle assessment on Indian leather production excluded farming from their system boundary and used economic allocation for meat processing [125].

- A study of Catalonian leather also used economic allocation, but included agriculture [126].
- First generation bio-based polymers:
 - Mass allocation was used for the co-products of corn wet milling and soybean oil milling in a comparison of PHA from corn dextrose and soy beans [23].
 - System expansion was used for the impacts of corn wet milling in other studies of PHA, taking into account the avoided environmental burdens of alternatives to wet milling co-products [24, 84].
 - The methodology published by APME (now PlasticsEurope) was used in developing eco-profiles for PLA [42, 78]. That methodology avoids the use of system expansion by substitution, instead suggesting mass or energy, stoichiometric and economic allocation as potential methods, depending on the goal of the production process [51, 127].
- Second generation bio-based polymers:
 - For a system producing PLA from municipal food waste, the only energy considered is that required for conversion of the food waste to PLA. Upstream production of the waste is not included [86].
 - An assessment of greenhouse gas emissions from producing PHA from industrial wastewater did not include upstream production of the waste water in the system boundary [26]. Additionally, only “non-renewable CO₂ emission equivalents” were evaluated, which could set a precedent for ignoring any animal methane emissions from farming.

Economic allocation is therefore common when using animal by-products, however the system boundaries are not consistent. System expansion has been

used for cradle to gate profiles of bio-based polymers, despite elsewhere being labelled inappropriate for such a study.

For first generation bio-based polymers, the systems utilise the main product of the agriculture and milling processes for conversion into polymer. Mass allocation is therefore likely to give more favourable results than other methods which allocate fewer impacts to less important co-products.

If it is assumed that the demand for bloodmeal can be met by blood supply from existing farming activities, the total emissions from farming can be assumed to be dependent on change in supply of meat, rather than change in supply of blood. This would justify a form of allocation where no energy use or greenhouse gas emission from farming and meat processing are attributed to bloodmeal or Novatein Thermoplastic Protein. Such a scenario results in considerably fewer emissions per kilogram of polymer than mass allocation, as will be seen below.

The unallocated impacts of farming and meat processing to produce 1 kg of bloodmeal, along with all other products, based on the data presented in the previous chapter are shown in Table 32.

Table 32: Total unallocated impacts of farming and meat processing for the 222 kg of live animal required to produce 1 kg bloodmeal.

	Total unallocated impact for all products	
	Non-renewable primary energy (MJ/kg bloodmeal)	Greenhouse gas emissions (kgCO ₂ e/kg bloodmeal)
Farming	1210	880
Transport of animals to the abattoir	354.4	14.1
Meat processing	22.2	1.5
	1586.7	895.6

6.2.3.1 Simple mass allocation

The simple mass allocation used in Chapter Five considered blood as a product of farming and meat processing, and then blood drying as conversion of that product into another product.

Only 15% of the mass of raw blood is recoverable in bloodmeal, meaning 6.67 kg of blood is needed to produce 1 kg bloodmeal. This leads to a high allocation of

impacts, effectively penalising bloodmeal with regard to farming and meat processing for its water content, then again for energy used to remove that.

The contributions of farming, transport to the slaughterhouse and meat processing to the environmental impacts of producing bloodmeal under this allocation scenario are shown in Table 33.

Table 33: Simple mass allocation of farming and meat processing to bloodmeal.

	Non- renewable primary energy (MJ/ kg bloodmeal)	Greenhouse gas emissions (kgCO ₂ e/ kg bloodmeal)
Farming	36.3	26.4
Meat processing	10.6	0.42
Transport of animals	0.67	0.046
Total	47.6	26.867

6.2.3.2 Mass allocation excluding wastes and losses

Where an output is partly co-product and partly waste, life cycle inputs and outputs should be allocated to the co-products part only [39]. The simple mass allocation above treats whole blood as a product and does not account for water being a waste, with regard to the production of bloodmeal. An alternative mass based allocation can be obtained by considering only the recoverable solids content of blood as a product. If this is the case, the proportion of the rest of the animal that is also waste should to be excluded from a share of the impacts as well. A new mass allocation result is obtained using the proportions of products from a whole animal shown in Figure 16.

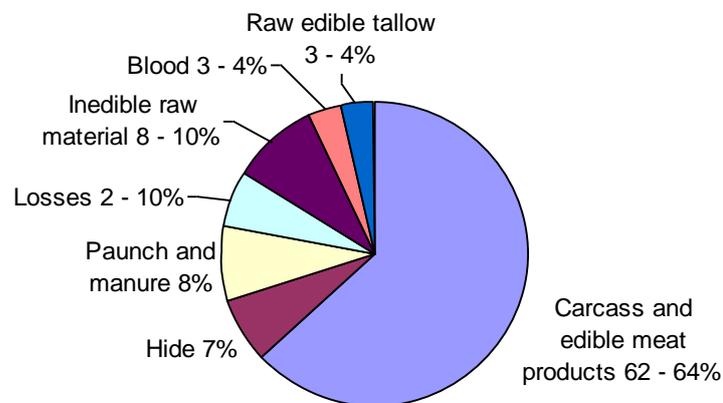


Figure 16: Composition of a 450 kg steer [34].

Assuming 6% losses and 8% paunch and manure along with the unrecoverable fraction of blood as waste, the remaining mass gives 0.83 kg products per kg live weight. The mass fraction of bloodmeal relative to total products is 0.00542. Using this as the allocation factor to divide the total impacts (Table 32) gives the impacts per kg of bloodmeal shown in Table 34.

Table 34: Mass allocation of farming and meat processing to bloodmeal, excluding wastes and losses from.

	Non- renewable primary energy (MJ/kg bloodmeal)	Greenhouse gas emissions (kgCO ₂ e/kg bloodmeal)
Farming	6.56	4.77
Meat processing	1.92	0.076
Transport of animals	0.12	0.0083
Total	8.60	4.85

6.2.3.3 Economic allocation

An economic allocation for farming and meat processing can be calculated using the price and yield of bloodmeal from a whole animal along with the price of a whole animal.

An average animal is assumed to have a 275 kg carcass weight and a 500 kg live weight [57]. Assuming a 15% recovery from raw blood and 3.5% of the live weight as raw blood the mass of recoverable blood meal per animal is $500 \times 0.035 \times 0.15 = 2.625$ kg. Using an approximate price of bloodmeal as \$1.00/kg as considered in the commercial feasibility study the value of this is \$2.63 [106]. An approximate price for an animal is \$5.00/kg_{cw} [128]. Using a 275 kg carcass weight, the value of the whole animal is \$1375.

The value of the bloodmeal recoverable from the animal is therefore only 0.2% of the value of the animal. This gives rise to an allocation factor of only 0.002, which can be combined with the total impacts per kg of bloodmeal (Table 32) and Equation 1 from Chapter Two. That is, of the impacts of a whole animal, only 0.002 should be allocated to the 2.63 kg bloodmeal produced. The contributions of farming, meat processing and transport of animals to non-renewable primary energy use and greenhouse gas emissions under this scenario are shown in Table 35.

Table 35: Economic allocation of farming and meat processing to bloodmeal.

	Non- renewable primary energy (MJ/kg bloodmeal)	Greenhouse gas emissions (kgCO ₂ /kg bloodmeal)
Farming	2.310	1.680
Meat processing	0.677	0.027
Transport of animals	0.042	0.003
Total	3.029	1.710

6.2.3.4 No allocation of energy or emissions to low value by-products

The function of blood drying could be considered to be two fold: Firstly the reduction of pollution that would occur if blood were released into the environment and secondly the production of bloodmeal as a marketable product. Blood is mainly dried from an environmental position and the generation of an additional income stream can be considered a fortunate bonus [33].

Such an approach is consistent with available energy usage data on rendering and blood drying. Energy usage is usually expressed in terms of the amount of raw material processed, rather than the amount of tallow, meat and bone meal or bloodmeal produced [117, 121, 129].

This is essentially the same as saying that production of blood is not a function of farming and meat processing. Rather, blood is a waste which poses a pollution problem. The function of blood processing is therefore conversion of a waste stream into product that can be sold. Under such an assumption, no greenhouse gas emissions or energy use of farming or meat processing should be attributed to bloodmeal. Blood drying itself should be included as there are other alternative treatments for blood that do not produce bloodmeal. For example, it has been shown that edible protein can be extracted from bovine red blood cells or red blood cells and plasma can be used to make higher value medical products [116, 130]. It should be remembered that for these other applications blood needs to be collected in a hygienic manner which is often not practical [34]. Likewise, transport of diluted blood to the rendering facility should also be included.

6.2.3.5 System expansion to avoid allocation

System expansion via substitution is avoided in the eco-profiles of petroleum derived polymers. Nevertheless, system expansion to avoid allocation is favoured

in the LCA standards and has been used in some cradle to gate studies of other bio-based polymers and is therefore considered here.

An alternative use of bloodmeal is as a nitrogen rich fertiliser. Dried blood for use as fertiliser contains 14% nitrogen by mass [131]. In a cradle to gate system where bloodmeal is used to make a thermoplastic it is not available to be used as a fertiliser. The energy and emissions required to fulfil the displaced function with a different product can be used as a substitute for the supply of bloodmeal.

To replace bloodmeal used to make NTP with a synthetic fertiliser, such as urea, requires fossil energy resources and the release of greenhouse gas emissions in the manufacture of that fertiliser. New Zealand produced urea requires 65 MJ/kg N non-renewable primary energy, with an associated release of 3.0 kgCO₂e/kg N [59]. The non-renewable primary energy and greenhouse gas emissions for enough urea to replace bloodmeal used in NTP are shown in Table 36.

Table 36: Non-renewable primary energy and greenhouse gas emissions for replacement of bloodmeal's fertilising function.

	Non-renewable primary energy (MJ/kg bloodmeal)	Greenhouse gas emissions (kgCO ₂ e/kg bloodmeal)
Replacement with synthetic urea	9.1	0.42

Blood drying alone uses 25.8 MJ/kg bloodmeal non-renewable primary energy and has emissions of 1.55 kgCO₂e/kg bloodmeal, even without including upstream impacts of farming and meat processing. This is around three times the energy and emission of producing urea to deliver the same amount of nitrogen as shown in Table 36. This supports the assumption that the intended function of blood drying is reduction of pollution from the meat industry, rather than production of a product.

It should be noted that bloodmeal is an “organic fertiliser” and synthetic fertilisers are not functionally equivalent with respect to use in organic farming. Nor does the calculation above take into consideration any difference in bio-availability of nitrogen from the two fertilisers.

6.2.4 Summary of allocation methods

Bloodmeal is the main ingredient in NTP and the impacts of producing NTP are dominated by the production of bloodmeal. The contribution of bloodmeal to non-renewable primary energy use in the production of NTP under the different allocation scenarios is shown in Figure 17. Simple mass based allocation gives the highest contribution. If mass allocation for farming and meat processing excludes waste streams from the masses considered, the contribution of farming and meat processing becomes a lot smaller. Economic allocation allocated less energy than either mass based scenario. This is because the value of the bloodmeal is very low compared to meat. Replacement of the fertilising function of bloodmeal with synthetic fertilisers uses less primary energy than is attributed to bloodmeal from blood drying, even before upstream impacts from farming and meat processing are allocated. Such a result cannot be used on an attributional basis for bloodmeal, but can be used when comparing systems where bloodmeal is used for different functions.

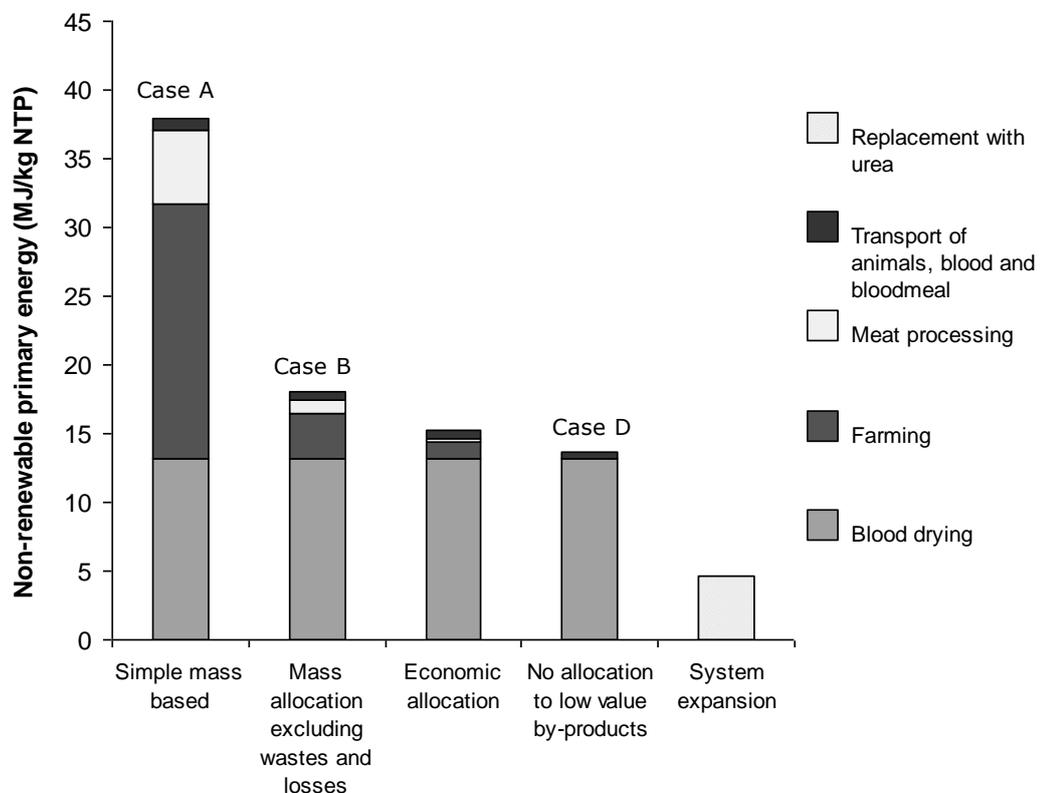


Figure 17: Contribution of bloodmeal to non-renewable primary energy demand of NTP production under different allocation scenarios for farming and meat processing.

Figure 18 shows the contribution of bloodmeal to the greenhouse gas emissions released in producing NTP under the different allocation scenarios. Using either of the mass-based allocation methods results in significantly higher emissions compared to the other scenarios. The proportional contribution of farming to greenhouse gas emissions of bloodmeal supply is higher than it is to non-renewable energy use. This is because greenhouse gas emissions from farming are dominated not by the combustion of fuel, but by emissions from animals.

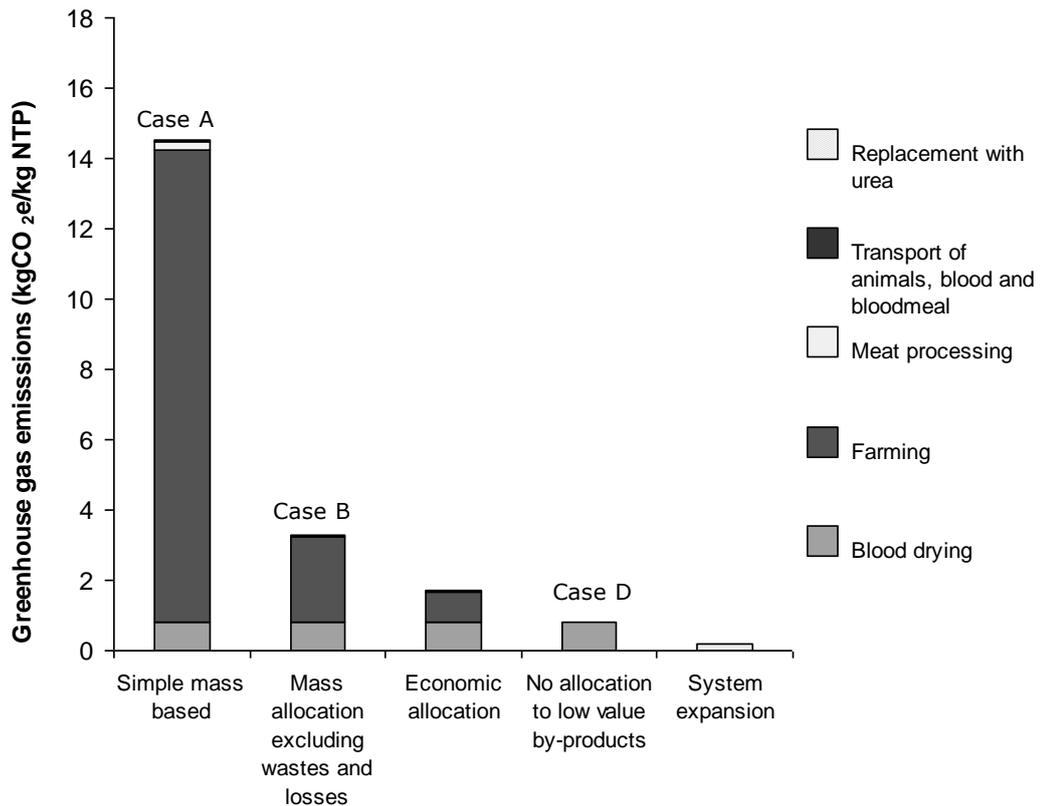


Figure 18: Contribution of bloodmeal to greenhouse gas emissions of NTP production under different allocation scenarios for farming and meat processing.

6.2.4.1 Consistency within allocation methods

In this study the stepwise procedure for allocation, as discussed in ISO 14041 has been followed [39]. As a result, rendering and blood drying operations have been separated from farming and meat processing. For rendering and blood drying, the impacts from energy supply have been correlated with the amount of material entering the plant to enable a mass allocation method. With farming and meat processing, the relationship between emissions or energy use and the mix of co-

products is more complicated, and a variety of allocation scenarios have been considered and evaluated.

6.2.4.2 Base cases for comparison with other bio-based polymers

To make comparison against other bio-based polymers, three of the above allocation scenarios have been considered. Additionally, for one allocation scenario (mass excluding waste and losses), two electricity generation assumptions have been included. The result is four Novatein Thermoplastic Protein cases for comparison, as outlined here:

- Case A: The case described at the end of Chapter Five, in which the impacts of farming and meat processing have been allocated based on the mass of raw blood.
- Case B: The recoverable solids content of blood is assumed to be a co-product of farming and meat processing, with the liquid fraction assumed to be a waste. Mass allocation is used between co-products. This simulates a situation in which the demand for NTP is greater than the supply of bloodmeal.
- Case C: The same allocation as situation A, but with electricity for rendering activities and NTP processing assumed to be supplied by coal fired generation.
- Case D: Low value by-product assumption, with no impacts of farming or meat processing allocated to bloodmeal. This simulates the situation in which bloodmeal supply is dependent on demand for meat products and is in excess with respect to the amount needed to produce Novatein Thermoplastic Protein.

These allocation scenarios have been chosen to correspond to allocation assumptions reported in the life cycle assessments of other bio-based polymers NTP is to be compared too. The contributions of each portion of the cradle to gate profile of these cases are outlined in Table 37 with more detail on case B, C and D respectively in Table 38, Table 39 and Table 40. Detail on Case A has already been presented in Table 31 in Chapter Six.

Table 37: Non-renewable primary energy use and net greenhouse gas emissions for cases A, B, C and D.

	Non-renewable primary energy use (MJ/kg)				Greenhouse gas emissions (kgCO ₂ e/kg)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
Supply of bloodmeal	37.93	18.06	20.99	13.68	13.488	2.273	2.612	-0.200
Supply of non-bloodmeal additives	9.20	9.20	9.20	9.20	0.462	0.462	0.462	0.462
NTP processing	1.16	1.16	3.06	1.16	1.160	0.079	0.305	0.079
Total	48.29	28.42	33.25	24.04	15.110	2.815	3.379	0.342

Table 38: Non-renewable primary energy use and greenhouse gas emissions for the production of 1kg Novatein Thermoplastic Protein, Case B.

Unit process	Non-renewable energy use			Greenhouse gas emissions (kgCO ₂ eq)
	Feedstock (MJ)	Process (MJ)	Total (MJ)	
NTP processing				
Process energy	n/a	1.160	1.160	0.076
Direct emissions	n/a	n/a	n/a	0.0087
	0.000	1.160	1.160	0.084
Non-bloodmeal additives				
Water supply	0	0.001	0.001	0.000
Urea manufacture	0.764	0.764	1.528	0.076
Sodium dodecyl sulphate	0	0.431	0.431	-0.003
Sodium sulphite manufacture	0	0.187	0.187	0.015
Triethylene glycol manufacture	2.135	3.348	5.483	0.211
Titanium dioxide manufacture	0	0.695	0.695	0.065
Transport of non-bloodmeal additives	n/a	0.560	0.560	0.039
	2.899	5.987	8.886	0.403
Production of bloodmeal				
Blood drying	0	13.16	13.16	0.791
Farming	0	3.341	3.341	2.43
Meat processing	0	0.979	0.979	0.039
Biogenic carbon content	n/a	na/	n/a	-1.027
Transport of animals, blood and bloodmeal	n/a	0.578	0.578	0.040
	0	18.058	18.058	2.273
Total	2.90	25.20	28.10	2.761

Table 39: Non-renewable primary energy use and greenhouse gas emissions for the production of 1kg Novatein Thermoplastic Protein, Case C.

Unit process	Non-renewable energy use		Total (MJ)	Greenhouse gas emissions (kgCO ₂ eq)
	Feedstock (MJ)	Process (MJ)		
NTP processing				
Process energy	n/a	3.064	3.064	0.296
Direct emissions	n/a	n/a	n/a	0.0087
	0.000	3.064	3.064	0.305
Non-bloodmeal additives				
Water supply	0	0.001	0.001	0.000
Urea manufacture	0.764	0.764	1.528	0.076
Sodium dodecyl sulphate	0	0.431	0.431	-0.003
Sodium sulphite manufacture	0	0.187	0.187	0.015
Triethylene glycol manufacture	2.135	3.348	5.483	0.211
Titanium dioxide manufacture	0	0.695	0.695	0.065
Transport of non-bloodmeal additives	n/a	0.560	0.560	0.039
	2.899	5.987	8.886	0.403
Production of bloodmeal				
Blood drying	0	16.09	16.09	1.069
Farming	0	3.341	3.341	2.43
Meat processing	0	0.979	0.979	0.039
Biogenic carbon content	n/a	n/a	n/a	-1.027
Transport of animals, blood and bloodmeal	n/a	0.578	0.578	0.040
	0	20.99	20.99	2.551
Total	2.90	30.04	32.94	3.259

Table 40: Non-renewable primary energy use and greenhouse gas emissions for the production of 1kg Novatein Thermoplastic Protein, Case D.

Unit process	Non-renewable energy use		Total (MJ)	Greenhouse gas emissions (kgCO ₂ eq)
	Feedstock (MJ)	Process (MJ)		
NTP processing				
Process energy	n/a	1.160	1.160	0.076
Direct emissions	n/a	n/a	n/a	0.0087
	0.000	1.160	1.160	0.08
Non-bloodmeal additives				
Water supply	n/a	0.001	0.001	0.000
Urea manufacture	0.764	0.764	1.528	0.076
Sodium dodecyl sulphate	0	0.431	0.431	-0.003
Sodium sulphite manufacture	0	0.187	0.187	0.015
Triethylene glycol manufacture	2.135	3.348	5.483	0.211
Titanium dioxide manufacture	0	0.695	0.695	0.065
Transport of non-bloodmeal additives	n/a	0.560	0.560	0.039
	2.899	5.987	8.886	0.403
Production of bloodmeal				
Blood drying	0	13.16	13.16	0.791
Farming	0	0	0	0
Meat processing	0	0	0	0
Biogenic carbon content	n/a	n/a	n/a	-1.027
Transport of animals, blood and bloodmeal	n/a	0.517	0.517	0.036
	0	13.68	13.68	-0.200
Total	2.90	20.82	23.72	0.288

6.3 Sensitivity Analysis

A sensitivity analysis was conducted to consider various assumptions made in compiling the inventory and impact assessment. The contribution of bloodmeal production varies greatly depending on the allocation method used for farming and meat processing which requires the sensitivity analysis to be conducted in two parts. The first part was the significance of various assumptions (including allocation method) on the impacts of Novatein Thermoplastic Protein from the supply of bloodmeal. The second part was the significance of various assumptions on the impacts for conversion of that bloodmeal into the bio-based polymer. Both parts considered the sensitivity of that portion of the life cycle to those assumptions, as well as the sensitivity of the overall cradle to gate system. The

unit processes included in each portion are identified in Figure 19 and have been named with respect to their relationship with bloodmeal, “supply” and “conversion.”

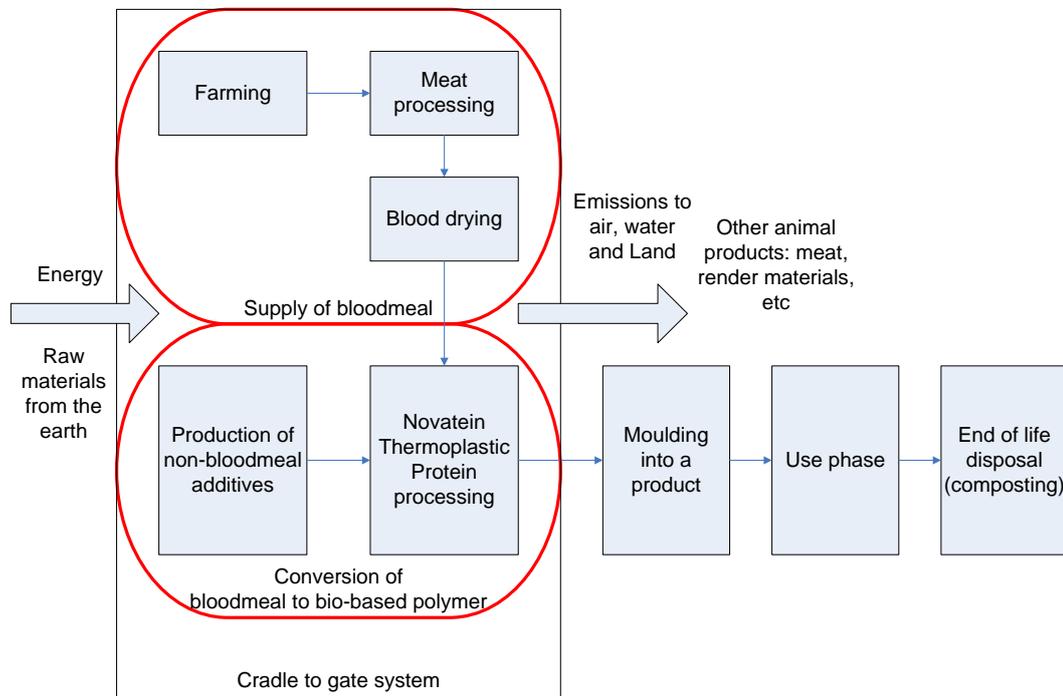


Figure 19: Division of cradle to gate life cycle for sensitivity analysis.

The reference scenario chosen for the sensitivity analysis is Case B that will be used for comparison with other bio-based polymers. This case has been chosen as it uses a mass allocation which is common in other assessments, but also follows the ISO 14041 guideline not to allocate any impacts to waste streams [39]. Additionally this case takes into account the choice of New Zealand as a location in its electricity assumption.

Contributions from different unit processes can be ranked based on their percentage contribution in each impact category. Ranking included in LCA standards suggests the following ranges [41]:

- Greater than 50% contribution – significant.
- Between 25% and 50% – relevant.
- Between 10% and 25% – some influence.

- Between 2.5% and 10% – minor.
- Less than 2.5% – negligible

Table 41 shows the contributions of various parts of the cradle to gate life cycle of NTP in Case B rated according to these rankings. When combining the processes involved in the production of bloodmeal, the influence becomes significant for both non-renewable primary energy and greenhouse gas emissions. Combined, the production of all non-bloodmeal additives has a relevant influence on non-renewable primary energy, and some influence on greenhouse gas emissions. Transport and NTP processing both have minor influences on the two impact categories.

Table 41: Percentage contribution of unit processes to overall non-renewable energy use and greenhouse gas emissions in reference scenario.

	Non-renewable primary energy use		Greenhouse gas emissions	
NTP processing				
Process energy	4.1%	Minor	2.7%	Minor
Direct emissions	n/a		0.3%	Negligible
	4.1%	Minor	3.1%	Minor
Non-bloodmeal additives				
Water supply	0.0%	Negligible	0.0%	Negligible
Urea manufacture	5.4%	Minor	2.8%	Minor
Sodium dodecyl sulphate	1.5%	Negligible	-0.1%	Negligible
Sodium sulphite manufacture	0.7%	Negligible	0.5%	Negligible
Triethylene glycol manufacture	19.5%	Some	7.6%	Minor
Titanium dioxide manufacture	2.5%	Negligible	2.4%	Negligible
Transport of non-bloodmeal additives	2.0%	Negligible	1.4%	Negligible
	31.6%	Relevant	14.6%	Some
Production of bloodmeal				
Blood drying	46.8%	Relevant	28.7%	Relevant
Farming	11.9%	Some	88.0%	Significant
Meat processing	3.5%	Minor	1.4%	Minor
Biogenic carbon content	n/a		-37.2%	Some
Transport of animals, blood and bloodmeal	2.1%	Minor	1.4%	Minor
	64.3%	Significant	82.3%	Significant
Total	100%		100%	

Assumptions made during the preparation of an LCA can be considered in a similar way. Assumptions that contribute a variance of greater than 10% (relative to Case B) can be deemed to be significant [41]. Assumptions regarding the production of bloodmeal and its subsequent conversion into a bio-based polymer are considered separately in the following sections:

6.3.1 Sensitivity of assumptions with regard to production of bloodmeal

Assumptions regarding the supply of bloodmeal include:

- The allocation method for non-renewable energy use and greenhouse gas emission of farming and meat processing.
- Electricity generation method for energy used in blood drying.
- Onsite energy demand for rendering activities and blood drying.
- The level of dilution of blood entering the drier.
- Inclusion of the carbon content of bloodmeal as a “credit,” that is, a removal of greenhouse gases from the atmosphere.

The effect of changing these assumptions on the non-renewable energy use and greenhouse gas emissions of supplying bloodmeal is shown Table 42.

Table 42: Sensitivity analysis for the supply of bloodmeal.

Case	NRPE (MJ/kg NTP)	Variance from base	GHGs (kgCO ₂ e/kg NTP)	Variance from base
Reference (Case B): Mass allocation excluding waste and losses.	18.06	n/a	2.27	n/a
Change to simple mass allocation (Case A).	37.93	110%	13.49	493%
Change to no allocation to low value by-products (Case D).	13.68	-24%	-0.20	-109%
Change to economic allocation.	15.22	-16%	0.67	-70%
Change of electricity mix for blood drying and thermoplastic processing to coal (Case C).	20.99	16%	2.55	12%
Exclusion of biogenic carbon credit.	18.06	n/a	3.30	45%
Heat and electricity demand for blood drying based on European data.	20.91	16%	2.37	4%
No dilution of blood.	13.67	-24%	1.97	-13%

Sensitivity to allocation method was investigated by comparing the results of the different allocation methods discussed earlier in the chapter to the reference case. The allocation method for farming and meat processing is the most significant assumption, with alternative assumptions causing a variance of between -24% and 110% for non-renewable primary energy use and between -109% and 493% for greenhouse gas emissions.

Sensitivity to the assumption about electricity was investigated by comparing the results when coal fired generation is assumed to provide the electricity for blood drying with the reference case. This is equivalent to Case D that will be used for comparison with other bio-based polymers. The assumption of coal fired electricity in blood drying causes a 16% variance in non-renewable energy use and as 12% variance greenhouse gas emissions for the supply of bloodmeal. Electricity generation is therefore a significant assumption with respect to this

portion of the life cycle. If bloodmeal is to be sourced internationally, the electricity supply in the country it is produced in therefore needs to be considered.

Sensitivity to the assumption that the carbon content of bloodmeal represents a removal of greenhouse gases from the atmosphere in a cradle to gate system was also investigated. This had no effect on non-renewable primary energy use, but exclusion of the negative greenhouse gas emissions representing causes net emissions to be 45% higher than in the reference case. In a full cradle to grave system, the carbon content of bloodmeal used for making Novatein Thermoplastic Protein could be assumed to be released back into the atmosphere. Omission of the “carbon credit” therefore can approximate a basic cradle to gate plus grave scenario, assuming that no additional emissions are generated in end of life disposal. This could then be compared to the cradle to gate plus grave system for thermoplastic starch for which non-renewable primary energy and emissions were obtained [13].

Sensitivity to data for blood drying was investigated by using an alternate energy demand of 120 kWh electricity and 2.4 GJ heat per tonne raw material as described in the best available techniques document published by the European Commission [121]. The alternate figure used was for blood drying only, rather than for a whole rendering facility, but the technological coverage was not clear. Different technologies for blood processing have different energy demands [33]. As such, it is not clear whether the variance is due to blood drying using a higher proportion of rendering plant energy, inherent variability between drying facilities or different drying technologies. The assumption is significant with regard to non-renewable energy demand, causing a 16% increase relative to the base case. The increase in greenhouse gas emissions is only 4% and therefore this assumption is not significant with regard to those.

Energy use in blood drying has been calculated on the basis of the amount of material entering the facility. Dilution of blood with washwater decreases the yield of recoverable solids and increases steam usage in drying [116]. A different yield of bloodmeal from the same amount of raw material would therefore cause a different result per kilogram of bloodmeal. A 10% yield of recovered bloodmeal from raw material was assumed in the reference case, based on information about

the facility visited [117]. The theoretical yield of bloodmeal recoverable from undiluted raw blood is 15%. If that yield is used, with the same energy demands per kg material entering the facility, the non-renewable energy use in bloodmeal supply is reduced by 24% relative to the reference case. Emissions are reduced by 13%. The assumption about the dilution of raw blood is therefore significant. The implication of this is that if blood could be collected more carefully, with a lesser degree of dilution, energy use and emissions from producing bloodmeal may be reduced.

As well as considering the effects of the above assumptions on bloodmeal supply, their effects on the entire cradle to gate process for producing Novatein Thermoplastic Protein were also evaluated as part of the sensitivity analysis. The results of this can be seen in Table 43.

Table 43: Sensitivity analysis for the supply of bloodmeal in the cradle to gate NTP system.

Case	NRPE (MJ/kg NTP)	Variance from base	GHGs (kgCO ₂ e/kg NTP)	Variance from base
Reference (Case B): Mass allocation excluding waste and losses.	28.10	n/a	2.76	n/a
Change to simple mass allocation (Case A).	47.97	71%	13.97	406%
Change to no allocation to low value by-products (Case D).	23.72	-16%	0.29	-90%
Change to economic allocation.	25.27	-10%	1.16	-58%
Change of electricity mix for blood drying and thermoplastic processing to coal (Case C).	32.94	17%	3.26	18%
Exclusion of biogenic carbon credit.	28.10	n/a	3.79	37%
Heat and electricity demand for blood drying based on European data.	30.96	10%	2.86	4%
No Dilution of blood.	23.72	-16%	2.46	-11%

All of the assumptions considered regarding supply of bloodmeal are significant for either non-renewable primary energy, greenhouse gas emissions or both. The system is most sensitive to the allocation method used. The same trends are seen

as for the supply of bloodmeal alone, symptomatic of bloodmeal supply dominating the cradle to gate profile in the reference case.

6.3.2 Sensitivity of assumptions with regard to the conversion of bloodmeal into bio-based polymer

Assumptions regarding the conversion of bloodmeal into Novatein Thermoplastic Protein include:

- Inclusion of plasticizer.
- Electricity generation method for energy used in NTP processing.
- Water supply.
- Inclusion of titanium dioxide in the formulation.
- Origins of feedstock used to produce sodium dodecyl sulphate.

The effect of changing these assumptions on the non-renewable energy use and greenhouse gas emissions of supplying non-bloodmeal additives and processing to product Novatein Thermoplastic Protein is shown in Table 44. Table 44 excludes the supply of bloodmeal to allow for a sensitivity analysis independent of the allocation method for farming and meat processing (see Figure 19).

Table 44: Sensitivity analysis for the conversion of bloodmeal to NTP (excluding bloodmeal supply).

Case	NRPE (MJ/kg NTP)	Variance from base	GHGs (kgCO ₂ e/kg NTP)	Variance from base
Reference (Case B).	10.05	0%	0.49	0%
Unplasticized formulation without triethylene glycol.	4.49	-55%	0.27	-45%
Assumption of 12% higher impacts from production of TEG.	10.70	7%	0.51	5%
Change of electricity mix for blood drying and thermoplastic processing to coal (Case C).	11.95	19%	0.71	45%
Californian water supply.	10.06	0.12%	0.49	0.15%
Omission of titanium dioxide.	9.38	-7%	0.42	-13%
Petroleum based sodium dodecyl sulphate.	10.68	6%	0.52	6%

To check the sensitivity regarding the inclusion of a plasticizer, the earlier formulation from the commercial feasibility study was used [106]. In this formulation, no plasticizer (TEG) was included and the mass fractions of the remaining components have been recalculated, and are shown in Table 45. The parts per hundred bloodmeal have remained unchanged from the reference case recipe (Table 8). The result of this is that the mass fractions of all other ingredients have increased.

Table 45: Composition of Novatein Thermoplastic Protein without TEG as a plasticizer.

Material	Mass Fraction (kg/ kg NTP)	Parts per hundred bloodmeal (pph _{BM})
Water	0.3403	60
Urea	0.0567	10
Sodium dodecyl sulphate	0.0171	3
Sodium sulphite	0.0114	2
Titanium dioxide	0.0075	1.3
Bloodmeal	0.5671	100
Novatein Thermoplastic Protein	1	176.3

From Table 44 it can be seen that this was the most significant assumption. The unplasticized formulation has a reduction of 55% non-renewable primary energy and 45% greenhouse gas emissions from this portion of the life cycle compared with the reference case.

Although such a reduction would seem beneficial, without additional plasticizers, the polymer may become brittle and unsuitable for its function when moisture is lost in the environment. The plasticized and unplasticized formulations are therefore not necessarily functionally equivalent.

Sensitivity to the selection of data source for plasticizer was also considered. As seen in Chapter Five, an alternative data source and calculation resulted in 12% higher non-renewable primary energy use for production of diethylene glycol. That same percentage change has been assumed for both non-renewable primary energy use and greenhouse gas emissions in the production of triethylene glycol to determine the significance of uncertainty in the plasticizer data. This change had no significant effect on non-renewable energy use or greenhouse gas emissions for the conversion of bloodmeal to NTP.

Sensitivity to impacts from water supply (which in the reference case were negligible) were investigated by using primary energy and greenhouse gas emissions for desalinated water [107]. Although the alternative data was for California, rather than New Zealand, this was used as a worst case estimate representative of water supply in areas where clean, fresh water is scarce. The variance was not significant.

Both the most energy intensive manufacturing method and the most greenhouse gas causing energy supply have been assumed for the production of titanium dioxide in the reference case. Under that assumption the contribution of titanium oxide to both impact categories is more than sodium dodecyl sulphate and sodium sulphite combined. Titanium oxide was added as a pigment and tracer for laboratory analysis, but is not always necessary for thermoplastic processing and could be left out in commercial production. The significance of doing so was investigated, recalculating non-renewable primary energy use and emissions for the formulation shown in Table 46.

Table 46: Composition of Novatein Thermoplastic Protein without titanium dioxide.

Material	Mass fraction (kg/ kg NTP)	Parts per hundred bloodmeal (pph _{BM})
Water	0.3077	60
Urea	0.0513	10
Sodium dodecyl sulphate	0.0154	3
Sodium sulphite	0.0103	2
Tri-ethylene glycol	0.1026	20
Titanium dioxide	0.0000	0
Bloodmeal	0.5128	100
Novatein Thermoplastic Protein	1	195

Despite the high non-renewable primary energy and greenhouse gas emissions assumed for titanium dioxide, the mass fraction within Novatein Thermoplastic Protein is so small that the variance in non-renewable primary energy is not significant. Omission of titanium dioxide does, however, reduce greenhouse gas emissions in this portion of the life cycle by 13%.

In the reference case it is assumed that sodium dodecyl sulphate is manufactured from plant based feedstock and includes a net reduction in greenhouse gases on a cradle to gate basis due to its biogenic carbon content. This assumption was investigated by replacing energy and emissions data with those for production of anionic alcohol sulphate surfactants from petroleum based feedstock in Germany [70]. This change does not significantly affect non-renewable primary energy use for the supply of non-bloodmeal additives and processing into NTP compared with the reference case.

As with assumptions regarding the supply of bloodmeal, assumptions about the conversion of bloodmeal into a bio-based polymer have also been evaluated for the entire cradle to gate system. The sensitivity of the cradle to gate system to these assumptions is shown in Table 47.

Table 47: Sensitivity analysis for the conversion of bloodmeal to NTP in the cradle to gate NTP system (including supply of bloodmeal).

Case	NRPE (MJ/kg NTP)	Variance from base	GHGs (kgCO ₂ e/kg NTP)	Variance from base
Reference (Case B).	28.10	0%	2.76	0%
Unplasticized formulation without triethylene glycol.	24.59	-12%	2.80	1%
Assumption of 12% higher impacts from production of TEG.	28.76	2%	2.79	1%
Change of electricity mix for blood drying and thermoplastic processing to coal (Case C).	32.94	17%	3.26	18%
Californian water supply.	28.12	0.04%	2.76	0.026%
Omission of titanium dioxide.	27.56	-2%	2.71	-1.8%
Petroleum based sodium dodecyl sulphate.	28.74	2%	2.79	1.1%

The supply of bloodmeal (farming, meat processing and blood drying) has the largest contribution to both impact categories in the reference case. Sensitivity to assumptions about the production of non-bloodmeal additives and NTP processing is therefore lessened when evaluated in the cradle to gate system including bloodmeal supply. Whether or not a plasticizer is included remains a significant assumption with regard to non-renewable primary energy use on a cradle to gate basis, but not with regard to emissions. The uncertainty from different data sources for the production of the plasticizer is not significant in the cradle to gate system.

Change in electricity assumption from a New Zealand average supply to an entirely coal based generation is significant for both non-renewable primary energy and greenhouse gas emissions in the cradle to gate NTP system.

Neither the use of a more energy intensive water supply, omission of titanium oxide nor the use of petrochemically derived SDS has a significant effect in the cradle to gate reference system.

6.3.3 Conclusions of sensitivity analysis

Across the cradle to gate production of NTP, the most sensitive assumption is the allocation method used for farming and meat processing. The conversion of bloodmeal to NTP is sensitive to the combination of additives used, in particular the energy required to produce the plasticizers instead of water. Omission of plasticizer approximately halves both the non-renewable primary energy use and greenhouse gas emissions for conversion of bloodmeal to NTP. On a cradle to gate basis, including the supply of bloodmeal, the inclusion or omission of plasticizers still had a significant influence on the eco-profile of NTP.

Both the production of bloodmeal, and its conversion to NTP are sensitive to assumptions about electricity. In the cradle to gate system the change in assumption to coal fired generation causes a 17% increase in non-renewable primary energy use and a 20% increase in greenhouse gas emissions. Therefore, if Novatein Thermoplastic Protein is produced internationally, with different electricity sources, it will have a different primary energy and greenhouse gas emissions profile from New Zealand production. For comparisons with other bio-based polymers, the coal based generation scenario was therefore included.

6.3.4 Inclusion of agricultural emissions

Depending on the allocation method used, agricultural emissions are the most significant contribution to greenhouse gas emissions in the production of Novatein Thermoplastic Protein. There is currently some debate as to the significance of agricultural emissions as a driver of climate change. It is argued that emissions from living creatures are part of the natural carbon cycle, and not man made. Rather, it is only greenhouse gas emissions from the displacement of carbon that was stored underground as fossil fuels to the atmosphere that we should be concerned with.

The flaws in this logic are as follows:

On a 100 year basis, methane has a 21 times higher effect per kg of gas, or 7.6 time higher effect per kg of carbon. Consequently, the conversion of atmospheric carbon dioxide to atmospheric methane contributes to an increase in radiative

forcing in the atmosphere. Although anaerobic processes producing methane are natural, farming of ruminant species in New Zealand is a human activity.

Once in the atmosphere, the distinction between fossil or biogenic origins does not affect the global warming potential of a gas, so it is the total contribution of greenhouse gases from all sources that contributes to climate change.

Under LCA practice all inputs and outputs of greenhouse gases should be included (although ones that cross the system boundary in and out as the same species and which can be assumed to be approximately equal can cancel each other out). As such, the amount of carbon contained in bloodmeal has been calculated as a removal of greenhouse gases from atmosphere, whilst emissions of methane by animals have been included as an emission.

6.4 Limitations of life cycle inventory

6.4.1 Data quality

Data presented in this study is from a variety of sources with differing levels of transparency regarding the underlying assumptions. Temporal, geographical and technological coverage for data is outlined in Table 48.

Table 48: Data quality assessment with regard to time, geography and technology.

Unit Process	Time related coverage	Geographical coverage	Technology coverage
Farming [57].	2007 report using 2003/2004 season	New Zealand	Representative of New Zealand average for non-dairy agriculture.
Meat processing [57].	2007 report using data from the 1994/1995 season	New Zealand	Representative of New Zealand average.
Rendering/ blood drying [117].	Current in September 2009	Specific plant	Representative of specific plant.
Urea Production [59].	2001	New Zealand	Representative of New Zealand's only urea manufacturer.
Sodium sulphite Production [111].	2007 Report	Europe	Representative of industry.
Sodium dodecyl sulphite production [23].	2003 Journal article	Unknown	Manufacture from palm oil.
Triethylene glycol production [112].	2003 Journal article reflecting production in 1995	Germany	Production of co-product (ethylene glycol).
Titanium dioxide production[115].	1999 Journal article	Europe	Worst case scenario based on most energy intensive technology.
Electricity production [68].	2009 report using 2008 data	New Zealand	Representative of New Zealand average.

6.4.2 System function and functional unit

This inventory and impact assessment is limited in that it only considers the production of Novatein Thermoplastic Protein and not its use to fulfil a function as a material or any additional functions possible in end of life disposal.

Within the cradle to gate system, upstream production of bloodmeal has a significant contribution to non-renewable energy use and greenhouse gas emissions. It is anticipated that at the end of its life Novatein Thermoplastic Protein will be disposed of via composting, to create a nitrogen rich compost. If the same fertilising activity as standard bloodmeal can be achieved after use as a plastic a system expansion without the need for synthetic fertilisers can be

considered. For example, the following two systems could be compared from cradle to grave:

- System A, bloodmeal used as fertiliser.
- System B, bloodmeal used to make NTP, displacing a petroleum polymer, then used as a fertiliser at the end of its life.

The impacts of farming, meat processing and blood drying will be common to both systems. When evaluating the difference in environmental consequences between them it is not necessary to quantify impacts from shared upstream unit processes. Inclusion of this additional function on a cradle to grave basis could therefore eliminate the allocation problem for NTP. The result is that none of the impacts of producing bloodmeal need to be included in the comparison between NTP and other polymers in such a cradle to grave scenario. The non-renewable primary energy and greenhouse gas emissions associated with production of Novatein Thermoplastic Protein in such a system would then be 10.0 MJ/kg and 0.49 kgCO_{2e}/kg respectively.

6.4.3 System boundaries

This assessment has been performed on a cradle to gate basis. A full life cycle assessment includes a cradle to grave system, incorporating usage of a product and disposal at the end of its useful life.

Factors that may influence non-renewable primary energy use and emissions relating to the use of products made from Novatein Thermoplastic Protein include:

- Density.
- Strength.
- Distance of from NTP plant to product manufacturing plant.
- Energy and other materials used in the product.
- Transport during use phase.

- Weathering – affects how many times a product can be reused for the same function.

Factors that may influence non-renewable primary energy use and emissions during end of life disposal include:

- Transport to disposal site.
- Biodegradability and compostability of NTP.
- Disposal method chosen.
- Whether Novatein Thermoplastic Protein can fulfil the alternative function of bloodmeal as a fertiliser.

6.4.4 Uncertainty analysis

A full uncertainty analysis is not feasible in life cycle assessment [45]. Nevertheless, a consideration of sources of uncertainty in an assessment is suggested as helpful by the LCA standards in explaining and supporting conclusions [39].

Uncertainty in life cycle assessment can arise from data, from decisions and from relationships used for interpreting data [123]. Table 49 describes uncertainties from data, Table 50 uncertainty from choices and Table 51 uncertainty from relationships used in this assessment.

Table 49: Sources of uncertainty from data used in assessment.

Data	Source of uncertainty	Comments
Farming and meat Processing	Only one data source, based on 2003/2004 season for farming and 1995/1996 season for meat processing.	Data source includes estimate of uncertainty of $\pm 34\%$ for farming of and $\pm 25\%$ for meat processing.
Blood drying	Site specific data may not be representative of whole industry. Data based on whole plant rather than specific to blood processing.	Compared with international data for energy use in blood drying which was 33% higher.
Delivery of water		Impacts from water are so small as to be negligible.
Triethylene glycol	Data on co-product adapted based on ratio of reactant.	Alternative data source considered, and % variance on other co products considered as part of sensitivity analysis. Effect of this variance was insignificant.
Sodium sulphite	Mixture of different data sources to compile inventory.	Contribution of sodium sulphite to cradle to gate impacts is insignificant.
Sodium dodecyl sulphate	One data source with little transparency on process.	Sensitivity analysis included alternative process. Overall effect of change was insignificant.
Urea	New Zealand production assumed, but some urea is imported to meet demand.	
Titanium dioxide	Worst case assumed for energy demand and energy emissions.	Sensitivity is insignificant.

Table 50: Sources of uncertainty from decisions made when compiling assessment.

Choice	Source of uncertainty	Comments
Energy in NTP processing	Assumption that energy use is the same for different formulations.	Assumed that the difference in formulation has no significant effect on specific heat capacity of the polymer
Allocation method	Different allocation methods have large variances.	Sensitivity analysis has been performed. More than one method used for comparison with other bio-based polymers.

Table 51: Sources of uncertainty from relationships used in assessment.

Relationship	Source of uncertainty	Comments
Primary energy and emissions for production of electricity	NZ electricity varies.	Sensitivity analysis included two different assumptions.
Global warming potentials	Uncertainty in models.	Used IPCC model as used by other LCA practitioners.
Global warming potentials	New GWP100s available in more recent IPCC documents.	With the exception of non-methane volatile organic compounds from NTP processing (which have little significance on overall contribution) the global warming potentials from the IPCC's second impact report have been used. These are the ones used under the Kyoto protocol, by the MED in NZ, and in other assessments data was obtained from.

6.4.5 Limitations of life cycle impact assessment

Impact assessment has been limited to non-renewable primary energy and greenhouse gases. These often show a strong correlation with other impacts [83].

A limitation of only considering these impact categories is that the effect of blood processing on water pollution is not quantified. Under the assumption that blood is a waste from meat processing, removal of solids to produce bloodmeal would provide a credit with respect to biological oxygen demand and chemical oxygen demand. This credit would help justify the energy use and air emissions of the production of bloodmeal.

The life cycle impact assessment used in this analysis did not include the optional elements of normalisation, weighting and grouping, as these were not part of the goal of the study.

6.5 Comparisons with other bio-based polymers

As identified in the discussion on allocation methods, four cases with different assumptions have been chosen for comparison with other bio-based polymers.

Non-renewable primary energy use for the cradle to gate portion of the life cycle has been aggregated into three parts for comparison with other bio-based polymers.

- Production of biomass (including transport).
- Production of other additives (including transport).
- Production of polymer from the above materials.

Novatein Thermoplastic Protein is compared with thermoplastic starch, PLA and PHS. The case of thermoplastic starch was a cradle to gate plus grave assessment, including an assumption of incineration at the end of life [13]. For PLA two sets of data were obtained, one based on engineering estimates and a more recent assessment based on actual plant information. These assessments included consideration of the purchase of windpower credits to reduce non-renewable energy use and emissions associated with the production of electricity [42, 78]. For PHA three cases were considered. The first two cases used conventional energy, but different feedstocks (corn and soy) [23]. The third case used corn as feedstock, but utilised renewable energy [23, 84]. Figure 20 shows non-renewable primary energy use for the four Novatein Thermoplastic Protein scenarios and these other bio-based polymer systems. Where available in the literature, non-renewable energy data has been split into the same sections of the life cycle as used for Novatein Thermoplastic Protein, otherwise just a total has been included.

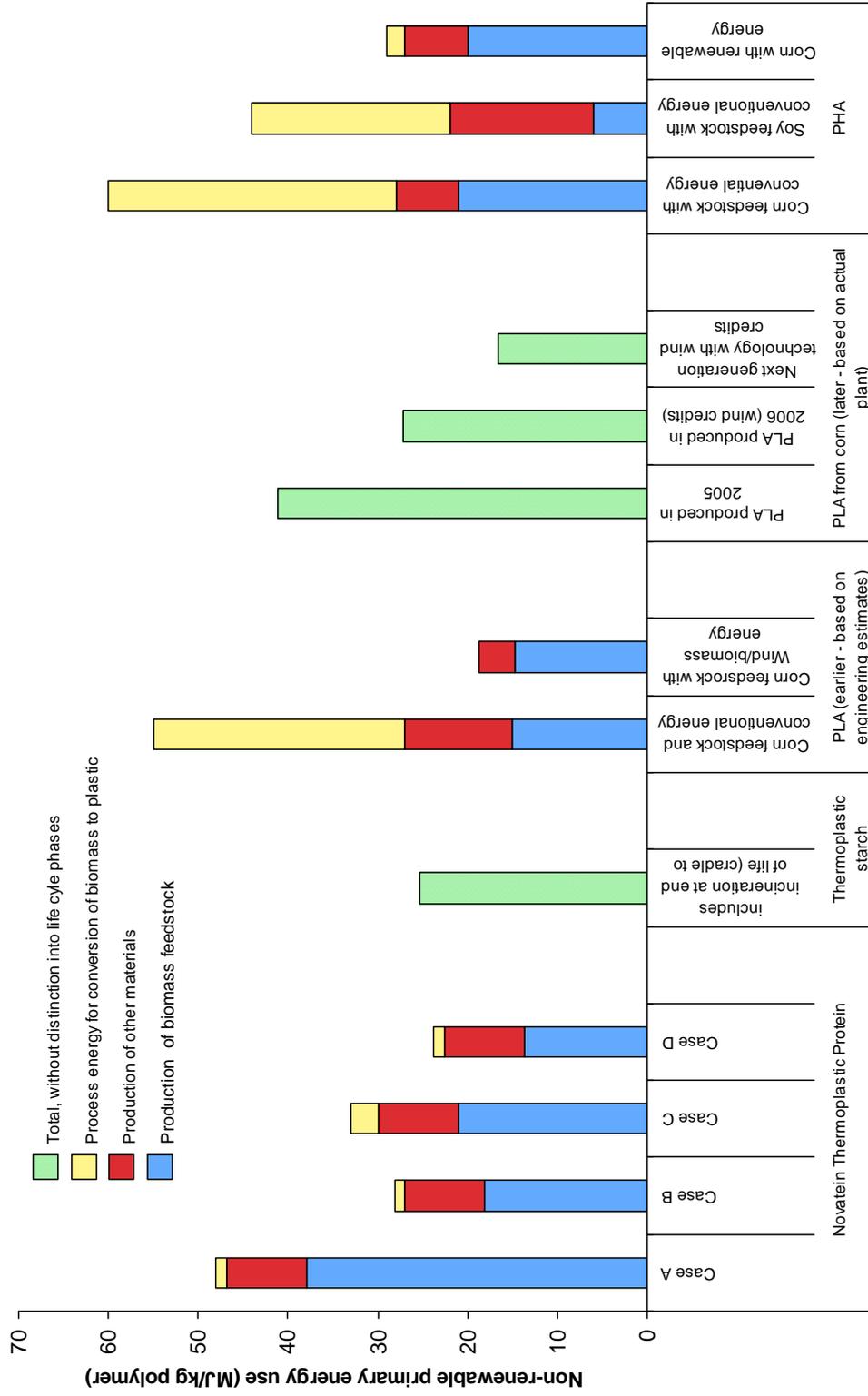


Figure 20: Cradle to gate non-renewable primary energy for Novatein Thermoplastic Protein and other bio-based polymers.

Process energy for the conversion of biomass to bio-based polymer only has a small contribution to the eco-profile of Novatein Thermoplastic Protein. This is in contrast to fermentation based polymers such as PLA and PHA for which this makes up approximately half the cradle to gate non-renewable energy demand when conventional energy is used. Figure 21 shows net greenhouse gas emissions for the same cases.

In cases A, B and C, with allocation of impacts from farming on a mass basis, the amount of emission calculated is greater than that reported for other bio-based polymers. In case A, the total emissions attributed to NTP are approximately an order of magnitude greater than other bio-based polymer systems considered. In contrast to plant based biomass the upstream production of animal biomass from ruminants produces more emissions than it absorbs. Inclusion of these on a mass allocation bases dwarfs emissions from other unit processes in the production of NTP.

In Case D the impacts of farming and meat processing are allocated entirely to main products and not to blood or bloodmeal. Emissions in such a case are comparable to those reported for PHA with conventional energy and less than those reported for PLA using conventional energy. Due to the uncertainty involved in performing an LCA and potential for different decisions in each system this does not necessarily mean that NTP produces fewer emissions per kg than PLA. Nonetheless, the relatively low process energy for conversion of bloodmeal to NTP and New Zealand's high proportion of low emission renewable electricity generation would suggest this is the case.

The thermoplastic starch case includes emissions from incineration at the end of the material's life. This releases any biogenic carbon content back into the atmosphere. Omitting the negative contribution to net greenhouse gas emissions of Novatein Thermoplastic Protein to allow for a more appropriate comparison with the thermoplastic starch case, case B has would have total emissions of 3.79 kg CO₂e/kg polymer.

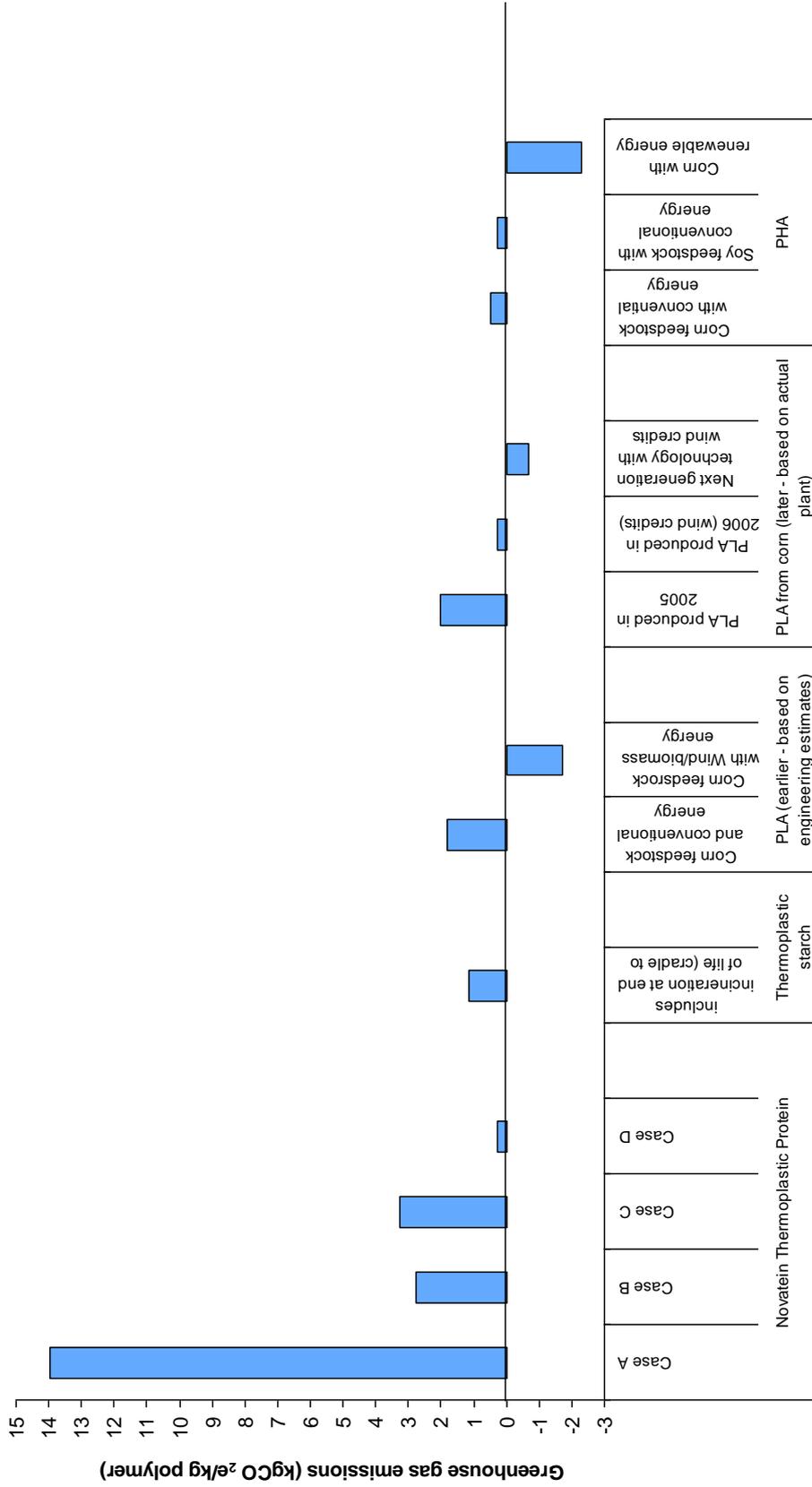


Figure 21: Cradle to gate greenhouse gas emissions for Novatein Thermoplastic Protein and other bio-based polymers.

These various bio-based polymers have differing material properties and therefore are not necessarily functionally equivalent. Additionally, decisions and assumptions made when performing LCA in these systems vary. As such, whilst an interesting benchmark, the comparisons included here cannot be used to assert superiority of any of these materials over the others.

In general, the energy and emissions involved in converting bloodmeal into Novatein Thermoplastic Protein are lower than manufacturing other bio-based polymers. It is only when the impacts of farming and meat processing and bloodmeal supply are included in some fashion that Novatein Thermoplastic Protein appears less favourable.

6.5.1 Comparison with producing petroleum based polymers

The motivation for producing bio-based polymers is as a replacement for conventional polymers. Therefore, whilst a comparison with other bio-based polymers provides a valuable benchmark, it is also important to consider the petroleum based polymer Novatein Thermoplastic Protein could replace. The material properties of Novatein Thermoplastic Protein are similar to low density polyethylene and these are therefore functionally equivalent in some applications [17].

In the reference scenario, Case B, production of Novatein Thermoplastic Protein uses 28.1 MJ/kg non-renewable primary energy, of which 2.9 MJ/kg represents the use for non-renewable feedstocks. The remaining 25.2 MJ/kg is for energy supply. Low density polyethylene uses 72.3 MJ/kg non-renewable primary energy, however, of this 48.6 MJ/kg represents the use of non-renewable feedstocks [92]. If, at the end of its life, polyethylene is incinerated with energy recovery, some of this can be recovered. This leaves 23.7 MJ/kg as being for energy supply. The amount of energy used, excluding the use of non-renewable feedstocks is therefore about the same for both materials.

In Case B, production of Novatein Thermoplastic Protein has been estimated to have net greenhouse gas emissions of 2.76 kgCO₂e/kg, more than the 1.89 kgCO₂e/kg of low density polyethylene. Based on case B one can conclude that the production of Novatein Thermoplastic Protein as a replacement for low

density polyethylene is justified as a way to reduce dependence on non-renewable feedstocks, but not as way of reducing greenhouse gas emissions.

Under an alternative scenario, as explored in Case D where no impacts of farming and meat processing are allocated to blood, the production of Novatein Thermoplastic Protein is attributed 0.29 kgCO₂e/kg. In this case, this is less than that emitted in producing an equivalent amount of polyethylene. If demand for bloodmeal to produce Novatein Thermoplastic Protein can be met by existing farming activities, such a scenario is justified. Therefore, replacement of low density polyethylene with NTP may contribute to a reduction in emissions. A full cradle to grave system would still be required to confirm this for specific products and end of life disposal methods.

The weathering and degradability properties of NTP are not the same as LDPE. This means there are applications that LDPE is suitable for, for which Novatein Thermoplastic Protein would not be a suitable replacement. The converse of this is that Novatein Thermoplastic Protein may be able to be disposed of in alternative methods at the end of its useful life that are not open to polyethylene.

6.6 Conclusions

The objectives of this life cycle assessment were the estimation of cradle to gate non-renewable energy use and greenhouse gas emissions that can be attributed to Novatein Thermoplastic Protein, identification of the largest contributions to that energy demand and emissions and comparison with other bio-based polymers.

The reference scenario, Case B, using a mass based allocation for impacts of farming and meat processing, attributed 28.1 MJ non-renewable primary energy and 2.76 kgCO₂e to the production of 1 kg Novatein Thermoplastic Protein.

Within the reference scenario the production of bloodmeal, accounts for more than half of the non-renewable primary energy use and greenhouse gas emissions on a cradle to gate basis. With non-renewable primary energy, it is blood drying that contributes the most, accounting for 47% of the total for the system. With emissions, it is farming that has the largest contribution, with 88% of the net emissions.

An alternate scenario can be considered in which blood is seen as a waste and not allocated any of the impacts of farming and meat processing. Under such a system, 23.7 MJ non-renewable primary energy and 0.29 kgCO₂e are attributable to the production of Novatein Thermoplastic Protein. In this scenario, blood drying has the greatest contribution to non-renewable energy use. Combustion of fuels to supply this energy becomes the greatest contribution to greenhouse gas emissions in this system.

Emissions per kilogram polymer in the reference system are greater than those for other bio-based polymers or conventional polymers obtained from literature. In the alternate system, emissions are less than for production of PLA or thermoplastic starch using conventional energy, but still higher than the net emissions for PLA or PHA production systems which make use of renewable energy in fermentation and recovery processes.

Impacts associated with the supply of energy for the conversion of biomass to bio-based polymer are only a small part of the overall contribution to environmental impacts for Novatein Thermoplastic Protein. This is in contrast to fermentation based polymers in which energy use in fermentation and recovery can account for greater than 50% of the impacts with regard to non-renewable energy use and greenhouse gases. In the reference scenario and the alternate scenarios, however, the total cradle to gate non-renewable primary energy use is of a similar order of magnitude to production of other bio-based polymers.

Whilst mass allocation reflects the attributional portion of the goal and scope, for decision making purposes, alternative allocation scenarios give additional insight. Replacement of the nitrogen fertilising function of bloodmeal with synthetic urea leads to smaller non-renewable primary energy demand and emissions than for blood drying alone. This gives support to the assumption that the production of bloodmeal is done as a form of waste treatment for meat processing, and that bloodmeal supply is dependent on demand for major products, such as meat. If excess bloodmeal is assumed, on a consequential basis, conversion of that bloodmeal to a thermoplastic protein bio-based polymer may use less non-renewable primary energy than some of the alternative polymers it may replace.

7 Conclusions

The objective of this thesis was to investigate the production of Novatein Thermoplastic Protein (NTP) using life cycle assessment. Specifically, this assessment sought to estimate non-renewable energy use and greenhouse emissions that can be attributed to NTP on a cradle to gate basis, to identify which parts of its manufacture have the greatest contribution, and to compare these results with the production of other bio-based polymers.

Non-renewable primary energy use and greenhouse gas emissions attributed to NTP were found to be most sensitive to the allocation method used to divide the impacts of farming and meat processing between bloodmeal and other animal products and by-products. With a simple mass allocation to raw blood as a product, emissions from farming dominated, contributing 96% of 13.97 kgCO₂e/kg NTP. Emissions from farming were 13 times higher than emissions credit assumed to be represented by the carbon content of bloodmeal. In such an allocation scenario, farming was also the largest contributor to non-renewable primary energy demand, contributing 39% of a total 47.97 MJ/kg NTP. Blood drying also had a relevant contribution to energy use, requiring 13.16 MJ/kg NTP. The production of non-bloodmeal additives was only 8.89 MJ/kg NTP, 2.90 MJ/kg NTP of which represented the consumption of non-renewable fossil resources as feedstock. Of all additives, water, despite having the largest mass fraction, had the smallest contribution. The plasticizer (TEG) had the largest contribution in both impact categories considered. The processing of bloodmeal together with these additives into NTP only contributed 1.16 MJ/kg NTP.

If allocation was based on the mass of bloodmeal that can be produced as a fraction of the mass of total products and co-products, excluding wastes and losses, a more realistic profile was obtained. Such a scenario more correctly follows the ISO guidelines suggesting impacts should not be allocated to waste, but only to co-products. In that case, 28.1 MJ non-renewable primary energy and 2.8 kgCO₂e greenhouse gas emissions could be attributed to the production of 1 kg NTP. Production of bloodmeal still had the largest contribution to both impact categories. Emissions from farming contributed 88% of the net greenhouse emissions, but it was blood drying that had the largest influence on energy use

(47%). Assuming coal fired electricity generation instead of the average NZ mix increased non-renewable primary energy for this allocation scenario to 32.94 MJ/kg NTP and greenhouse emissions to 3.33 kgCO₂e/kg NTP. This represented increases of 17% and 18% respectively.

As an alternative, blood was assumed to be a waste with regard to farming and meat processing and not allocated any impacts from them. There is a precedent in literature to treat low value by-products in this manner. The function of blood drying is therefore only to convert a waste stream into a product which can be sold, drying is therefore still included in the scope. It was found that blood drying and downstream thermoplastic processing attributed 23.72 MJ non-renewable primary energy, of which 2.90 MJ represented fossil feedstocks, to the production of NTP, along with 0.29 kgCO₂e greenhouse gas emissions. Even in such a scenario, the production of bloodmeal was still the largest contributor to both categories. For comparison, production of polyethylene uses 23.7 MJ/kg non-renewable primary energy for processes and consumes 48.6 MJ/kg non-renewable primary energy in fossil feedstock, with greenhouse gas emissions of 1.89 kgCO₂e/kg.

In contrast to fermentation based polymers, impacts associated with the supply of energy for the conversion of biomass to bio-based polymer are only a small part of the cradle to gate profile of NTP. Contributions other than the production of bloodmeal were found to be small, but within that group, plasticizer was most significant.

It was found that energy use was in a similar range to other bio-based polymers, however, if farming and meat processing were excluded NTP compared more favourably. If farming is included on either mass allocation basis it was shown that greenhouse gas emissions were higher than those of other bio-based polymers. If a simple mass allocation is used, emissions were shown to be an order of magnitude higher than for other polymers.

System expansion was also used to provide additional information on the LCA of bloodmeal production. Urea used to replace the nitrogen fertilising function of bloodmeal only required 4.7 MJ/kg NTP and released only 0.21 kgCO₂e/kg NTP. These are both less than those attributed to NTP by blood drying alone, even

when farming and meat processing are excluded. This could justify the conclusion that the primary motivation for blood drying is for waste treatment and that upstream impacts in the production of bloodmeal should be excluded from the system boundaries. However, the existence of other treatment options for blood, some resulting in higher value products, suggests that blood drying should be included. Furthermore, if it is assumed that the driving force for farming and meat processing is demand for products such as meat, then the total impact of farming and meat processing will be independent of the use of bloodmeal to produce NTP. Such an assumption is reasonable if NTP is only produced from the existing bloodmeal supply.

It was concluded that the most appropriate allocation scenario is to only attribute the impacts of blood drying (and associated transport) to bloodmeal, and not any impacts from farming and meat processing. Under such a scenario, the production of NTP has the potential to reduce non-renewable primary energy use and greenhouse gas emissions by replacing synthetic polymers or other bio-based polymers. For each potential application, however, a full cradle to grave life cycle system should be considered to ensure that impacts from the use and end of life phases do not outweigh any differences in impacts from manufacture.

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Appendices

List of abbreviations

°C	Degrees Celsius
BM	Bloodmeal
BOD	Biological oxygen demand
CED	Cumulative energy demand
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalents
COD	Chemical oxygen demand
DEG	Diethylene glycol
EECA	Energy Efficiency and Conservation Agency
GHGs	Greenhouse gas emissions
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
kg	Kilogram
kgkm	Kilogram kilometre
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MAF	Ministry of Agriculture and Fisheries
MED	Ministry of Economic Development
MJ	Megajoule
MoRST	Ministry of Research, Science and Technology
NRPE	Non-renewable primary energy
NTP	Novatein Thermoplastic Protein

PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PLA	Poly lactide
PM ₁₀	Particulate matter of 10 microns or less
pphBM	Parts per hundred bloodmeal
SDS	Sodium dodecyl sulphate
TBP	Taranaki By-Products Limited
TEG	Triethylene glycol
TEG	Triethylene glycol
TiO ₂	Titanium dioxide
TPS	Thermoplastic starch

Glossary

Acidification	A life cycle impact category reflecting production of acid rain.
Attributional LCA	The use of LCA to investigate how environmental impacts relate to an amount of function.
Bio-based polymer	A polymer manufactured, directly or indirectly, from biological feedstock.
Biodegradable polymer	A polymer that biodegrades on a relatively short time scale. Standards govern the rate required for a material to be labelled biodegradable.
Biological oxygen demand	A quantitative measure of water pollution, based on oxygen demand due to biological degradation processes.
Bioplastic	A commonly used term for polymers that are either biodegradable, manufactured from biological feedstocks, or both.
Biopolymer	A commonly used term for polymers that are either biodegradable, manufactured from biological feedstocks, or both.

Blood drying	The rendering operation that separates blood into bloodmeal and wastewater.
Bloodmeal	Dried blood from the meat processing industry.
By-product	An output of a process, other than the main desired products, that fulfils a useful function.
Carbon dioxide equivalents (kgCO _{2e})	The unit used when aggregating emissions of different greenhouse gases using GWP.
Category endpoint	The change to the environment investigated in a particular impact category.
Category indicator	A quantifiable representation of the change to the environment investigated in an impact category.
Characterisation factor	Amount of change to the environment per unit of an LCI inputs or output.
Characterisation model	A model of the environmental mechanism by which an LCI input or output causes change to the environment.
Climate change	A life cycle impact category reflecting the human contribution to global changes to the climate.
Compostable polymer	A polymer which is able to be disposed of and broken down by microbes in a commercial composting facility. Standards govern the rate required for a material to be labelled compostable.
Consequential LCA	The use of LCA to investigate how environmental impacts will change in response to a decision.
Co-product	Different products of a process that has more than one desired output.
Cradle	Extraction of raw materials from the earth.
Cradle to gate	Description of a scope that begins with extraction of raw materials from the earth and ends with a product or material ready to be shipped from the factory.
Cradle to grave	Description of a scope that begins with extraction of raw materials from the earth and ends with disposal of wastes at the end of a product's life.
Cumulative energy demand (CED)	The total primary energy required to be extracted from the earth for a system, including upstream processes.

Delivered energy	Energy used directly in a process, not including the upstream production and delivery energy.
Diethylene glycol (DEG)	A polar molecule which can be used as a plasticizer. A co-product of ethylene glycol and triethylene glycol.
Eco-profile	The results of life cycle inventory and impact assessment for the cradle to gate portion of a product's life cycle.
Elementary flows	Flows in or out of the system boundary with no further human intervention.
Emissions to air	Elementary flows released into the atmosphere.
Emissions to water	Elementary flows released into watercourses or bodies of water.
End of life disposal	Final disposal of a product once it has fulfilled its function. Some examples for polymers are landfill, incineration or composting.
Energy input	Any energy required by a unit process.
Energy output	Any energy recoverable from a unit process.
Environmental impacts	Changes to the environment investigated by LCA.
Eutrophication	A life cycle impact category reflecting buildup of nutrients in land or water.
Feedstock energy	The primary energy removed from the earth represented by fuels which are not combusted to generate energy, but instead used as feedstock and incorporated into a product.
Gate to gate	Part of the life cycle that begins with the arrival of material inputs at a factory and ends with a product or material ready to be shipped from the factory.
Global warming potential (GWP)	A quantitative measure of the effect of greenhouse gases on radiative forcing. Usually expressed relative to the effect of carbon dioxide, which is defined as having a GWP of one.
Goal	The objective of a life cycle assessment study, including its recipients and intended applications.
Goal and scope definition	The phase of LCA in which the objectives and scope of the study are defined.

Greenhouse gas emissions	Emissions of gases that contribute to global climate change.
Hot spots	The portions of a life cycle that have the most significant contribution to environmental impacts.
Impact category	A type of change to the environment investigated by an LCA.
Indicator result	The common units of results for an impact category in LCIA.
Initial system boundaries	The processes included in the initial scope of an LCA study. These may need to be revised as the LCA is performed iteratively.
Intermediate	A product of one unit process, used as an input into another.
Kilogram kilometre (kgkm)	Unit for transport in an LCA, representing a mass moved a distance.
Life cycle	All processes involved in fulfilling a function from cradle to grave.
Life cycle assessment	An internationally standardised method for investigating environmental impacts of a product from cradle to grave.
Life cycle impact assessment (LCIA)	The phase of LCA in which LCI data is related to changes to the environment.
Life cycle interpretation	The phase of LCA in which results of LCI and LCIA are evaluated and conclusions are made.
Life cycle inventory (LCI)	The phase of LCA in which data on material and energy flows are collected for unit processes included in the scope.
Low value by-product	By-products of a process that are of low economic value relative to the main product.
Material input	Any quantity of substance that enters a unit process.
Material output	Any quantity of substance that exits a unit process.
Meat processing	The slaughter and subsequent processing of an animal to produce useful products. In this assessment rendering operations are considered as a separate, downstream unit process.

Net greenhouse gas emissions	The net result of emissions of greenhouse gases and removals of greenhouse gases from the atmosphere.
Non-renewable primary energy (NRPE)	Primary energy from non-renewable sources. This includes fossil fuels such as oil, gas and coal, and nuclear energy.
Novatein Thermoplastic Protein (NTP)	A thermoplastic material produced from proteins found in bloodmeal.
Plasticizer	A low molecular weight additive for a polymer used to reduce interactions between chains increase processibility and improve material properties.
Polyhydroxyalkanoates (PHA)	A class of thermoplastic materials produced inside living cells and which can be produced by bacteria in fermentation processes.
Polyhydroxybutyrates (PHB)	The most commonly studied group of polyhydroxyalkanotates.
Poly lactide (PLA)	A thermoplastic material produced by polymerising lactic acid, a fermentation product.
Polymer	A chemical made up of long chains of repeating units.
Primary energy	Energy removal from the earth. Includes delivered energy, and upstream use and losses in the production and delivery of that energy.
Process energy	Energy used to conduct a process and not incorporated into the products.
Product	The main desired output of a process.
Product system	All the activities required for delivery of a function using a product.
Protein degradation	Destruction of protein structure at the level where the chains themselves a broken.
Protein denaturing	Destruction of protein structure at the level where interactions between protein chains are overcome, but the chains themselves remain intact.
Radiative forcing	A measure of the effect on the energy balance of the earth and atmosphere due to factors that influence climate.

Raw material	With regard to a specific unit process, it is something that enters it, with regard to the entire system, can refer to raw materials from the earth
Rendering	Processes used to separate water, protein and fat to produce animal by-products such as meat and bonemeal, tallow and bloodmeal.
Renewable primary energy (RPE)	Primary energy from renewable sources. This includes windpower, biomass, hydroelectricity and solar energy.
Scope	The systems and data types included in an LCA.
Thermoplastic	A polymer that undergoes a reversible transition from glassy solid to rubbery melt upon heating, and hence can be processed using extrusion and injection moulding.
Thermoplastic protein	Protein that has been modified with the addition of chemicals and plasticisers allowing processing with thermoplastic techniques.
Thermoplastic starch	Starch that has been modified with the addition of chemicals and plasticisers allowing processing with thermoplastic techniques.
Triethylene glycol (TEG)	A polar molecule used as a plasticizer. A co-product of ethylene glycol and diethylene glycol.
Unit process	The smallest unit for which life cycle inventory or impact assessment data is collected for.
Waste	Undesired outputs of a process.