Compostable Products in Aotearoa New Zealand

Report drafted by:

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For:

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Contents

List of Abbreviations

Acronym	Explanation
BBP	Benzyl butyl phthalate
BPA	Bisphenol A
BPI	Biodegradable Products Institute
CMA	Compost Manufacturing Alliance
DCHP	Dicyclohexyl phthalate
DBP	Dibutyl phthalate
DEP	Diethyl phthalate
DEHP	Di-(2-ethylhexyl) phthalate
DHEXP	Di-n-hexyl phthalate
DIBP	Diisobutyl phthalate
DINP	Diisononyl phthalate
DPENP	Di-n-pentyl phthalate / Diamyl phthalate
GC-MS	Gas chromatography - mass spectrometry
HDPE	High Density Polyethylene
FTOH	Fluorotelomer alcohols
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PC	Polycarbonate
PCL	Polycaprolactone
PE	Polyethylene
PES	Polyester
PFAS	Per- and polyfluoroalkyl substances
PFAA	Perfluoroalkyl acid
PFBA	Perfluoro butanoic acid
PFBS	Perfluoro butane sulfonate
PFHxA	Perfluoro hexanoic acid
PFHxS	Perfluoro hexane sulfonate
PFOA	Perfluorooctanoic acid
PFOS	Perfluoro octane sulfonic acid
PFPeA	Perfluoro pentanoic acid
PHA	Polyhydroxy alkanoate
PHB	Polyhydroxy butyrate

Acronym	Explanation
PHBH	Poly-3-hydroxybutyrate-co-3-hydroxyhexanoate
PHBV	Polyhydroxy butyrate valerate
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
RSL	Regional Screening Level
TOF	Total organic fluorine
TPS	Thermoplastic starch
UV	Ultraviolet

Summary

This report summarises the findings of a comprehensive literature review concerning the potential ramifications of compostable products on soil health. The report emphasises the distinctive attributes of examining soil health through a Te Ao Māori (Māori worldview) lens, thereby enriching policy considerations for compostable products in Aotearoa New Zealand. The review findings reveal substantial gaps in current knowledge, highlighting the necessity for further investigation.

We provide a series of key findings integrated into a structured framework. This framework is designed to offer guidance to stakeholders in their decision-making processes concerning compostable products. Ascertaining and addressing existing data and knowledge deficiencies is important in refining the suggested framework. This refinement process, proposed as Part 2 of the project, could encompass the introduction of thresholds for additives and forward-looking decision-making strategies to enhance the global relevance of the framework.

1 Introduction

With the Ministry for the Environment announcing its second phase of banning a range of single-use plastic items in Aotearoa New Zealand from July 2023 (Ministry for the Environment, 2023), there is an increasing need to explore alternatives to single-use plastics that are safer for the environment and people of Aotearoa New Zealand. Although the phase-out of single-use service-ware, plastic grocery bags and fruit stickers is a good start to addressing Aotearoa New Zealand's waste problem, there is limited knowledge and understanding of the environmental impacts that accompany the use of alternative products. Elimination of single-use items or the ability to reuse products should be the preferred solution; however, there are situations where this is simply not feasible. In such cases, compostable products may emerge as the preferred alternative.

As the use of the term 'compostable' becomes popularised, there is widespread confusion regarding its definition, the composition of compostable products and compostability conditions.

Ensuring the production of high-quality compost that does not have a negative impact on soil health is of utmost importance, especially considering the significant role of agriculture in Aotearoa New Zealand's economy and Te Ao Māori.

This report has been compiled in alignment with the compostable products position statement of the Ministry for the Environment, incorporating its central ideas and recommendations. The purpose of this report is to provide support for the creation of a compostable product framework ('the framework') that serves as guidance for the successful implementation of compostable product solutions in Aotearoa New Zealand, with a particular focus on additives in compostable products and their potential impacts on soil health. Through collaboration with diverse community and industry stakeholders, policymakers and relevant scientific experts, this report aims to:

- Present and compare how compostable products are addressed through global policies, standards and certifications.
- Summarise chemical additives used in compostable products and the current knowledge of their possible environmental impact, with a focus on soil health.
- Include Aotearoa New Zealand specificity – incorporating Te Ao Māori, relevant socioeconomic characteristics and infrastructure that may impact composting strategies.

Several suggestions for the path ahead are made at the end of this report based on current global knowledge while recognising the unique context of the Aotearoa New Zealand market. These are also incorporated into the framework to guide the decision-making process for compostable product users. Important knowledge and data gaps are highlighted, particularly those that impact the finalisation of the framework.

2 Terminology

2.1 Definitions

The following definitions have been identified as important and relevant for establishing Aotearoa New Zealand's composting landscape.

Bio-based plastics – Plastic where its materials are from renewable resources as opposed to petroleum. They are not necessarily biodegradable or compostable. (European Commission, 2022)

Biodegradable – Materials that naturally break down via microbial action with no specified timeframe or specific environmental conditions (unless specified alongside this term). Many, but not all, biodegradable products are compostable. (European Commission, 2022)

Bioplastic – This overarching term can also encompass bio-based and/or biodegradable plastics. Not all bioplastics are compostable. (Australian Bioplastics Association, 2019)

Compostable – Materials that have been certified to decompose completely to their basic components of water, natural gas and biomass within a specific timeframe and conditions. The timeframe and conditions required determine whether this is on an industrial or home/community scale. All compostable products are biodegradable. (Good Start Packaging, 2023)

Oxo-degradable – Plastics that are enriched with additives that accelerate their fragmentation. This can be triggered using heat energy or UV radiation. These products are not compostable. (Deconinck & De Wilde, 2013)

Oxo-biodegradable – Similar to oxo-degradable, however, once in small enough fragments, they can be accessed by microbes for partial or complete microbial degradation. (Hickford, 2022)

Polymer blends and composites – Blends refer to mixing two or more polymers to create a single phase. Composites refer to mixing a polymer with a non-polymer component such as fibres, ceramics or other additives. (Kulshreshtha & Vasile, 2002).

2.2 Terminology Relevance

Currently, there is a strong drive for the packaging industry to promote more sustainable products; however, not all brands or businesses possess correct or sufficient information about their products. Consequently, advertising may be based on limited knowledge of the environmental impact of their products. There is also a risk of greenwashing to improve customer sales. Greenwashing refers to the practice of communicating misleading and deceptive claims about the environmental performance of a product (Delmas & Burbano, 2011).

There is a need for correct and clear communication of end-of-life (EoL) expectations and environmental claims for compostable products, including regulations. The EoL of compostable products also needs to be clearly identified by the user and composting facilities to avoid accidental contamination of waste streams, such as placing a compostable product into a recycling bin. In 2021, the Ministry for the Environment published a survey report stating that while 55% of respondents said they currently compost, 61% found it confusing as to what you can and cannot compost. In addition:

- 34% thought it was okay to accidentally put a few non-compostable items in the compost (41% disagreed, with 25% on the fence or unsure).
- 71% of respondents said they recognised packaging is compostable by information on the package.

These figures illustrate the importance of clearly defining the terms associated with compostable products and removing vague or ambiguous terminology.

Environmental claims must be accurate and able to be substantiated by evidence that reflects scientific and technological developments. Misleading terms such as ‘eco-friendly’, ‘eco-conscious’ or ‘green’ are emotive and vague (WasteMINZ, 2019). Without sufficient substantiation, these terms lack specificity about the product's environmental attributes and thus can deceive consumers about the reliability of these claims. Other terms, such as ‘bioplastic’, are also too generic to provide consumers with informative details (Plastics NZ, 2023). Organisations such as the Advertising Standards Authority (ASA) encourage the Aotearoa New Zealand industry to take responsibility to ensure legal, decent and honest advertising communication to consumers. For example, under Principle 2 of the Advertising Standards Codes, advertisements claims, such as biodegradable, must be truthful, balanced and not misleading or likely to mislead, deceive or confuse consumers. It is also important to emphasise the need for the industry to abide by consumer law (Commerce Commission New Zealand, 2020).

Biodegradable and compostable terms are often used interchangeably when advertising products. These terms, from a regulatory perspective, have quite different meanings, as all compostable materials are biodegradable, but not all biodegradable materials are compostable. With no specified conditions indicated for the breakdown of biodegradable materials, the process may take longer and, therefore, may not meet composting timeframes. Factors that affect the timeframe of the degradation in terms of exposure conditions include moisture, pH, temperature, UV radiation, availability of oxygen and specific microorganisms (Bharagava, 2015). This distinction is, therefore, significant to those who are processing these materials as it affects processability and the final compost product. Biodegradability and composability claims must also be backed up by international standards and display the specific environment it is intended for and whether this relates to a part of or the whole product (Commerce Commission New Zealand, 2020).

2.3 Soil Health

Soil health is a complex concept that has been defined as the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems (The Intergovernmental Technical Panel on Soils (ITPS), 2020). Manaaki Whenua – Landcare Research recently highlighted that maintaining soil health requires the consideration of a wide range of functions that soils perform, including retention and cycling of nutrients, climate regulation, supporting biodiversity and production of food and forage (Stevenson et al., 2022). Assessing soil health requires consideration of the biological, physical and chemical components of the soil, as well as their interactions.

The addition of compost can modify and often improve many aspects of soil health. For instance, long-term field experiments conducted in the United Kingdom revealed that the regular addition of compost to soil increases the amount of soil organic matter, nutrients, soil microbial biomass, and the earthworm population (Litterick, 2017). Compost addition also decreases the bulk density of soil, which in turn can increase water and gas infiltration rates, soil biological activity and root penetration. This highlights the complexity of assessing soil health (Litterick, 2017). Recent studies have also highlighted the risk of introducing harmful chemicals to the soil through the leaching of chemicals from compostable products and their additives (Bridson et al., 2021; Bridson et al., 2023; Choi et al., 2019).

In this report, the scope of the discussion related to soil health is limited to chemicals entering the soil through the matured compost generated from compostable products. Conducting a thorough assessment of soil health is a multifaceted endeavour, demanding the ongoing monitoring of numerous parameters, preferably conducted in the field. Our current understanding of the global impact of compostable products on soil health remains severely limited, as outlined in Section 3.3. This knowledge gap largely results from scientific studies and standards that typically only consider a limited set of criteria, e.g. plant germination and assessments of toxicity to earthworms.

There is growing recognition of diverse social perspectives on soil health, which underscores the need for a more comprehensive approach to soil health and related policies. This broader perspective moves beyond the utilitarian viewpoint of soil primarily as a provider of ecosystem services, which is the prevailing Western-centric approach (Stevenson et al., 2022). Many indigenous cultures, including Te Ao Māori, adopt a more holistic and integrated perspective on soil health, as expounded in Section 4.4 of our report.

3 Compostable Products

Understanding how compostable products degrade in and affect different environments is of paramount importance when deciding how to approach plastic product alternatives. This includes understanding what types of chemicals and additives may be used for the functionality of alternative products.

3.1 Types

About half of Aotearoa New Zealand's compostable products promoted as suitable for home or commercial composting are fibre-based. Compostable fibre products (including paper/cardboard, sugarcane/ bagasse plates, and bamboo cutlery) easily break down and contribute carbon to compost if not mixed with non-compostable additives. Compostable plastics fall into the five categories shown in Figure 1 (Deconinck & De Wilde, 2013).

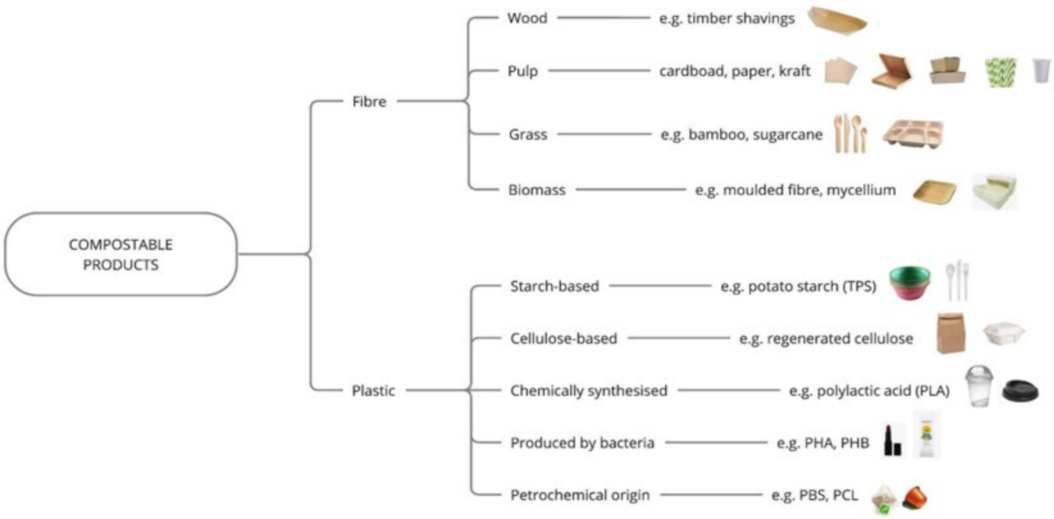

Figure 1. *A schematic showing the different categories of compostable product types.*

Fibre-based

Fibre-based compostable products are shown in Figure 1. They can be synthesised using diverse sources, including reused elements like newspaper and cardboard and natural fibres such as wood pulp, bamboo, bagasse, mycelium, and wheat straw. Their primary applications lie within the construction, chemical, food and beverage sectors.

Starch-based

Starch-based plastics are composed primarily of starch derived from potatoes, corn, rice or grains like wheat. They are heat resistant and have the potential to be biodegradable in many environments, including both industrial and home composting. There are challenges to the widespread use of starch-based plastics, such as cost and the potential for water sensitivity, as starch is a carbohydrate that is highly soluble in water, so products made primarily from starch are susceptible to water damage.

Cellulose-based

Biodegradable plastics can be made from natural cellulose fibres, regenerated cellulose and modified cellulose. Regenerated cellulose simply refers to cellulose that has been chemically processed before being 'regenerated' in a different form. Modified cellulose refers to a change in the functionality of natural cellulose through chemical alterations. Although cellulose-based products can biodegrade in various environments, chemically altered variants do not consistently comply with compostability certifications.

Chemically-synthesised

This category includes one of the most commonly known biodegradable plastics, polylactic acid (PLA), among many others. Although the building blocks of PLA are sourced from renewable sources, to enhance the desirable properties of this polymer, it is often mixed with non-renewable materials. PLA can be processed in industrial composting conditions or anaerobic digestion (above 50-55°C); however, it is important to note that while PLA itself will degrade in these conditions, the blends/composites may not.

Produced by bacteria

Bacteria can produce PHA, a polymer with desirable thermoplastic and water-resistant properties. The rigidity and malleability of the material can also be altered by changes to the bacteria diet to produce copolymers such as PHB, PHBV and PHBH. Although producing these materials comes with high energy and cost, they show biodegradability across a wide range of conditions, including industrial/home composting and anaerobic digestion.

Petrochemical origin

Some biodegradable plastics are based on building blocks synthesised from petroleum sources. This includes common polymers such as PBS, PCL, and PBAT. The only EoL option for these polymers is industrial composting, with biodegradability in other environments unclear.

3.2 Biodegradation

A multitude of factors can affect the ability of products to biodegrade. This includes both the composition of the material as well as the environment it is exposed to. In terms of the biodegradation of compostable products, this can be achieved in both anaerobic and aerobic conditions.

Most compostable products need environments such as a high temperature (on average 65°C) and sufficient moisture to achieve biodegradation within 90 days (Ecoware, 2021). This is where home composting and industrial composting differ. Industrially compostable products are designed to biodegrade in the optimal conditions of an industrial composting plant with high temperatures and in the presence of oxygen.

Home compostable products are designed to biodegrade in the conditions of a well-managed home composter at lower temperatures than in industrial composting plants. However, the rate of biodegradation will be slower and vary from house to house.

Aside from industrial composting, another processing technology used in some countries to process food waste is anaerobic digestion (MFE, 2022). Anaerobic digestion is a biochemical process occurring without the presence of oxygen, converting organic materials to methane and carbon dioxide. By comparison, composting is an oxygen-driven process. Due to the difference in degradation pathways, material suitable for composting may not necessarily degrade under anaerobic conditions in digesters. Some bioplastics can be degraded in digesters, while others cannot.

Vermicomposting is another composting method relevant to Aotearoa New Zealand. This involves the conversion of biodegradable waste into vermicompost (nutrient-rich material) via earthworms and other microorganisms. Various feeds, including anaerobic digested sludge, can be used for vermicomposting as long as ammonia concentrations are not high enough to pose toxicity to earthworms (Mynoke, 2022).

3.3 Impact of Compostable Products on Compost Quality & Soil Health

While many scientific studies report on the degradation of compostable materials and their impact on compost quality, only a very limited number of studies consider the impact of the compost produced on soil health. Some of these laboratory and field scale studies are summarised in Tables A1 and A2, respectively (see Appendix). A range of short-term ecotoxicity endpoints were considered when creating these tables, including phytotoxicity, toxicity to earthworms, microbial activity, and structure. Overall, the impact of compost produced with the inclusion of some compostable products is difficult to ascertain. This was largely due to differences in exposures (e.g. how the compost was produced, the proportion of plastic added) and/or endpoints (e.g. the species used, the effects measured and their environmental implications), leading to a general lack of consistency in the results.

Of particular interest to this report are the conclusions of a large project recently funded by the New South Wales Environmental Trust that looks at the impact of compostable plastics on compost quality and soil health (Williams, 2021). Real-scale experiments were conducted with two compostable plastics (PBAT film and PLA cutlery) added at a realistic rate (0.5% w/w) in a small-scale composting facility (~50 t/week), followed by extensive ecotoxicity testing. Results showed that the compostable plastics did not have an overall impact on the physicochemical characteristics of the compost produced (noting that the compost had a degree of heterogeneity). Terrestrial toxicity assessments of the compost produced indicated a negative impact on the growth of earthworms and the root length of wheat. There was no apparent impact on a range of other endpoints tested for earthworms and wheat or for other terrestrial species, including nematodes and microorganisms. The authors recommend that full chemical disclosure of the compostable plastics, including additives, would aid assessment of the fate and effects of these chemicals. Subsequently, it may reduce the requirement for additional toxicity assays and associated resource requirements.

3.4 Additives

3.4.1 Functional Additives

Functional additives are auxiliary or additive substances that are added during the manufacturing process of compostable products. All such additives have not yet been fully evaluated for their environmental impact (Bridson et al., 2023). Figure 2 illustrates the purpose of the most common additives found in compostable products.

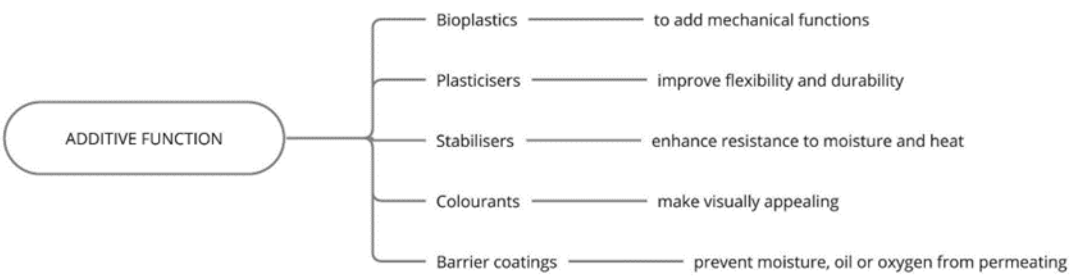

Figure 2. *A schematic showing the function of different common product additives.*

In addition to the aforementioned additives, supplementary materials may be employed during the conversion of polymers and papers into disposable items, including adhesives, coatings, and printing inks. These materials are composed of a mixture of chemicals. Therefore, instead of focusing on the materials, the subsequent discussion's scope is confined to chemical categories commonly linked with compostable products.

3.4.2 Additives - Chemical Classes and their Environmental Impact

A literature review regarding additives in compostable products reveals a significant knowledge gap. Williams et al. (2021) estimated that the contribution of chemical components, such as trace metals, from compostable plastics to compost products is likely to be very small (<0.12%) due to the small proportion of compostable plastics relative to food and green waste (estimated to be <0.25% in Australia). However, this assessment was not possible for the chemical components of compostable plastics that could not be identified or where no guideline limits from relevant standards exist. An additive can affect the soil environment in multiple ways, including direct impacts through leaching during composting, as well as indirect impacts through the release of non-biodegradable or partially biodegraded additives from the rest of the compostable product as it biodegrades, introducing these additives into the compost and soil. Hence, there is a need to further evaluate the quality and consequences of compost following the introduction of compostable products. It is recommended that comprehensive assessments encompassing various composting methods (composting, vermicomposting, anaerobic digestion) and production scales aligned with Aotearoa New Zealand's infrastructure are conducted. Identifying instances where specific compostable products might lead to environmental impacts will aid in defining acceptable thresholds for the associated additives. Figure 3 summarises the common chemical classes of additives potentially present in compostable products. The following sections summarise the knowledge available for each chemical class and their environmental impact.

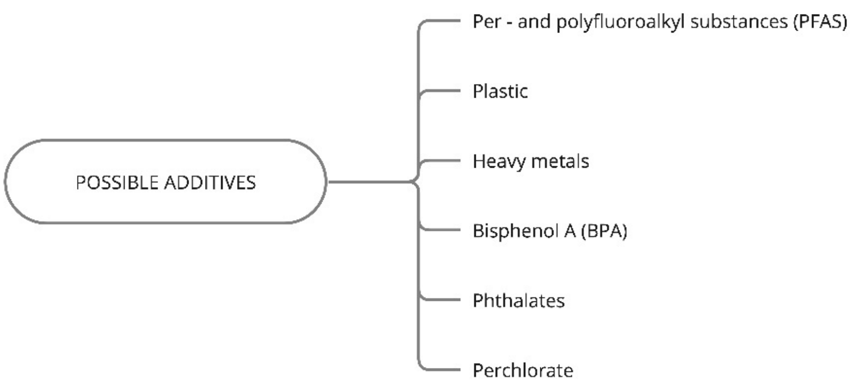

Figure 3. *A schematic showing the potential chemicals used in compostable products.*

3.4.2.1 PFAS

PFAS are synthetic chemicals characterised by strong carbon-fluorine bonds enabling desirable properties of heat stability, degradation resistance and water/grease repulsion. These are often called 'forever chemicals' due to their incredible stability in the environment. The most well-known category of PFAS, PFAAs, include PFOS, PFOA and PFHxS. A range of precursors can also transform into PFAAs in the environment.

In compostable products, PFAS can be added either through surface or internal sizing. Surface sizing involves coating materials with PFAS while internal sizing refers to adding PFAS to the pulping tanks with fibre suspensions before moulding into the desired shape (Glenn et al., 2021). Examples of commonly used products that have been shown to contain PFAS are dessert/bread wrappers, food contact paper and paperboard (Schaider et al., 2017), moulded fibre plates, paper straws (Moos, 2021), and corrugated pizza boxes (Nestler et al., 2019). Intentional or unintentional use of PFAS in compostable products can contribute to PFAS in the resulting compost. A recent study (Choi et al., 2019) found that PFAS from compostable food containers contributed to PFAS detection in composts from facilities accepting these containers. Another study specific to Canadian fast food service ware found that moulded bowls contained high levels of fluorinated compounds with the presence of 4-15 different compounds in each sample, including degradation products of FTOH (Schwartz- Narbonne et al., 2023). PFAS is also found in paper and plant-based drinking straws (Timshina et al., 2021).

PFAS & Soil

Numerous studies have found that compost that has included compostable food products as input contains considerably more PFAS than those with only organic inputs. One recent study found that older composts from 2014-2017 had greater concentrations of long-chain PFAS compared to those from 2019 and later, which have higher levels of short-chain PFBA, PFPeA and PFHxA (Goossen et al., 2023). However, there was 25-45 times more PFAS in these compost samples compared to those made with predominantly food waste. The most common PFAS found was 6:2 FTOH.

PFAS do not degrade during composting processes, and their occurrence in the end product (compost, anaerobic sludge, worm casting) is of high concern due to their reported effects on soil quality. There is evidence that PFAS can bioaccumulate in soil biota such as earthworms (Eisenia fetida, Eisenia andrei, Lumbriculus terrestris, Metaphire guillelm) and in plants growing on contaminated soil (Burkhard & Votava, 2023; He et al., 2016; Wang et al., 2020). PFAS are extremely persistent, and their accumulation will inevitably negatively affect soil biota (Cousins et al., 2020). For instance, the presence of PFAS in soil has been linked to reduced biodiversity (Cao et al., 2022) and a negative impact on soil bacteria through oxidative/DNA damage, as well as disruption of the cell membrane (Liu et al., 2016).

Specific PFAS thresholds for soil contamination levels have not historically been set for compost. With increasing knowledge of the persistence and toxicity related to these chemicals, there is a consensus that specific PFAS levels must be minimised to protect soil health. For example, prior to 2022 in Maine (US), the application of biosolids to land was restricted, with levels of PFBS, PFOS, and PFOA not permitted to exceed 1900, 5.2 and 2.5ppb, respectively. A complete ban was put in place in 2022 (Maine Department of Environmental Protection, 2018). PFOS soil guidance was also released, suggesting that PFOS levels as low as 6.4ppb can harm the meat or dairy industry through forage uptake (Maine Department of Environmental Protection, 2020).

Existing Guidelines

In 2018, Washington banned the intentional use of the entire class of PFAS in food packaging, with New York following suit the following year (Glenn et al., 2021). The BPI Certification Scheme (BPI, 2023) and CMA (Compost Manufacturing Alliance, 2023) created rules, which took effect in 2020, that restrict the presence of fluorinated compounds in their certified packaging. Their rules include:

1. Safety data sheets with all ingredients declared and displaying no presence of fluorinated chemicals.
2. Tests completed at a BPI-Approved lab show a maximum of 100ppm of Total Organic Fluorine (TOF).
3. A signed statement by the manufacturer confirming no intentionally added fluorinated chemicals.

In a recently released industrially compostable materials certification scheme, EN13432, self-declaration that no PFAS or other organic, fluorinated chemicals are intentionally added or are intentionally used during the production process is required (European Bioplastics, 2023). Most of the other certifications restrict the levels of total organic fluorine in compostable products. Since 2020, Denmark has prohibited (by law) the intentional use of short and long-chain PFAS in compostable service ware; however, they do allow the use of PFAS if a barrier is created to prevent PFAS migration into food (Danish Veterinary and Food Administration, 2020). Threshold levels are set at 20ppm TOF per kg of material. Compared to the BPI/CMA, Denmark’s maximum level is set five times lower, demonstrating that they have much less tolerance for the presence of PFAS in compostable service ware. Note that these guidelines were defined to limit human exposure to PFAS when using service ware and are therefore not suitable when the objective is to protect soil health.

A starting point for deriving guidelines relevant to composting and soil health is the recently released ecological soil guideline values presented in the latest PFAS National Environmental Management Plan for Australia and Aotearoa New Zealand (NEMP, 2023). By understanding the application rate of mature compost to the soil, it can be possible to back-calculate threshold values for compostable products.

3.4.2.2 Plastics

Plastic is a ubiquitous contaminant. Despite the promotion and use of biodegradable plastics, marketed as compostable, the degradation of these products is known to produce micro-/nanoplastics. During the degradation of biodegradable plastics, the plastic type has an influence on the formation of secondary particles, which are mostly smaller than 50μm. (Tong et al., 2022). Plastics come in the form of fragments, fibres and particles of various quantities and sizes. Tong et al. (2022) found that the thickness of material determines the number of particles produced and thus the degradation rate; thicker means fast mechanical abrasion but slow photo-oxidation.

Plastic & Soil

The results of a study quantifying microplastics in municipal solid waste showed a concentration of plastic impurities in the 10–30 items/g of dry compost range (Edo et al., 2022). The concentration of small fragments and fibres (equivalent diameter <5mm) was in the 5–20 items/g of dry weight range and was dominated by fibres (25% of all particles <500μm). Five polymers represented 94% of the plastic items: PE, PS, PES, PP, PVC, and acrylic. The Plastics Lab, a Canadian laboratory researching microplastics, recently discovered approximately 18 plastic particles in 1kg of compost (Ocean Wise, 2022).

Once in the soil, microplastics can affect the biophysical environment of the soil, affecting the bulk density, capacity for water retention, soil texture and relationships between the activity of microbes and soil aggregates (De Souza Machado et al., 2018). In addition, they can accumulate and concentrate pollutants such as BPA, antibiotics, heavy metals, and aromatic hydrocarbons (Tong et al., 2022). However, no threshold values are currently available for them in the literature.

3.4.2.3 Heavy Metals

Heavy metals in compostable products can arise from various sources:

- **Raw materials** – if the feedstock used to produce compostable products contains heavy metal contaminants, it can transfer those metals into the final product.
- **Additives** – some compostable products may include additives or colourants containing heavy metal impurities to enhance specific properties or aesthetics.

- **Production process** – inadequate quality control or contamination during manufacturing can introduce heavy metals into compostable products.

Heavy Metals & Soil

Extensive research has been conducted on the toxicity of heavy metals (Zhao et al., 2022), with evidence of the adverse effects on soil health well-established. All compostable certifications/standards include heavy metals with a maximum limit on their presence in the products (see Section 4). For example, the US, Australian, and EU standards restrict the levels of various heavy metals in compostable products.

3.4.2.4 Bisphenols

Bisphenols, including BPA, are a class of chemical compounds commonly used in the lining of food/drink products, for example, food wrapping (PVC or PE), bottles (PP, PC, HDPE) and other general plastic packaging (Vilarinho et al., 2019). It is a well-known additive in plastics and an environmental pollutant due to its xenoestrogen properties that cause it to interact with estrogen receptors in animals. Other bisphenol analogues, such as bisphenol S, bisphenol F, bisphenol AP and bisphenol AF, also show similar potential toxicity (Feng et al., 2016) and most exhibit higher biodegradability resistance (EFSA Scientific Committee, 2013).

BPA & Soil

In terms of soil health, a study conducted on mung bean (Vigna radiata) showed concentrations of 750mg BPA/kg dry soil after 14 days and 21 days of exposure has implications for the growth of the plant (Kim et al., 2018). Root development was also inhibited at a dosage of 1000 mg BPA/kg dry soil (Kim et al., 2018). Under aerobic conditions, BPA is expected to have a half-life of 3-37.5 days, whereas anaerobic soils showed no BPA degradation within 70 days (Careghini et al., 2015). Concentrations of BPA in the soil are highest in areas in which irrigation systems use wastewater amended with biosolids (Careghini et al., 2015). There is little evidence that BPA accumulates in soils as it is readily transported through soil layers (Careghini et al., 2015). BPA has also been found in various fresh fruits and vegetables, such as lettuce and collards, with the highest concentration ranges measured in the roots (441.7 and 199.6µg/kg f.w. respectively). Root concentration was 2-3 orders of magnitude greater than those in the stems and leaves (Dodgen et al., 2013).

Although few studies have been undertaken on the relationship between BPA and compost and compostable products, it can be inferred that because of the well-known human toxicity implications, it is a potential additive of concern for product materials. As BPA has begun to phase out and be replaced by other bisphenols, it is recommended that testing should be conducted on all bisphenol groups.

3.4.2.5 Phthalates

Phthalates refer to a group of chemical compounds commonly used as plasticisers to improve the flexibility and malleability of plastic products. They are also used in printing inks and lacquers. Phthalates contain the basic structure of an esterified benzene dicarboxylic acid with two alkyl chains, this being chemically stable in the environment. In terms of compostable products, phthalates have been found in products made from regenerated cellulose (Fierens T et al., 2012) and starch-based PBAT/PLA (Zhong et al., 2023), with Di-(2-ethylhexyl) phthalate (DEHP) being found in the highest concentrations and was the most abundant compound.

Phthalates & Soil

Phthalates are not bound to the product, so they can potentially migrate to whatever media they are in contact with (Fasano et al., 2012). Phthalates can migrate into the soil and thus have the potential to influence soil health. Existing studies indicate that the fate and impact of phthalates are dependent on the chemical nature of the phthalate - smaller molecular mass phthalates being less manageable but having a larger impact on microbial respiration (Cartwright et al., 2000). Degradation rates have been shown to be dependent on the alkyl chain length; DEHP takes longer to degrade compared to DEP. For phthalates to become toxic to microorganisms, the concentration would have to exceed 1mg/g, which is only associated with spill events or highly contaminated environments (Cartwright et al., 2000).

Existing Guidelines

Although not specific to soil, the United States and Europe have set phthalate thresholds in regard to risks to human health. As of 2018, children's toys and childcare articles must not contain more than 0.1% of any of the following phthalate compounds: DINP, DPENP, DHEXP, DCHP, and DIBP (Consumer Product Testing Company, 2023). The US Congress has also put into legislation that DEHP, DBP and BBP are not to exceed 0.1% individually of the total weight of the product. Since 2020, the European Union has restricted DEHP, DBP, DIBP and BBP use in a concentration equal to or above 0.1% by weight (European Commission, 2016).

3.4.2.6 Perchlorate

Perchlorate is an inorganic anion that contains one chlorine and four oxygen atoms. It is predominantly used in dry ingredient products as an anti-static agent (Maffini et al., 2016). It is often undeclared on labels despite it being present in food items since its approval in 2005. Its toxicity stems from its ability to disrupt the function of the thyroid by reducing hormone production. Low thyroid leads to poor brain development and a decrease in the human intelligence quotient (Steinmaus, 2016). Between 2008-2012 it was found that the dietary intake of perchlorate from food was 23% and 34% more for toddlers and infants, respectively, compared to pre-FDA approval (Abt et al., 2018).

Perchlorate & Soil

Perchlorate cannot be adsorbed on soil particles; however, it can be trapped once dissolved within soil pores (ITRC, 2008). Once present, it can be degraded biologically by organisms containing perchlorate reductase or superoxide chlorite enzymes (Acevedo-Barrios et al., 2019). As perchlorate travels down the soil horizons, organic matter in the surrounding environment decreases, thus allowing perchlorate to infiltrate groundwater before its degradation. Perchlorate can also change the soil chemistry, causing accelerated mineral dissolution, which increases the potential uptake of trace or heavy metals into soils and water mediums. It can, therefore, be assumed high perchlorate contamination is likely to be associated with high metal concentrations (Kumarathilaka et al., 2016).

Existing Guidelines

The US EPA’s Regional Screening Levels (RSLs) for perchlorate is 55mg/kg for residential and 820mg/kg for industrial. (Department of Toxic Substances Control, 2022). However, these won’t be directly applicable to Aotearoa New Zealand, due to different environmental conditions, health and safety regulations, and the availability of scientific data.

4 Global Policies

The compostability of a product can be certified through certification bodies located worldwide. Compostability standards are separated into industrial, home compostable, other environments and oxo-degradation. The environments and the certification bodies are shown in Table 1.

Table 1. *Certification bodies available for plastics in various environments. (Deconinck & De Wilde, 2013)**

Environment	Certification body
Industrial compostability	European Bioplastics (Europe) Vinçotte (Belgium) DIN CERTCO (Germany) Biodegradable Products Institute (USA) Cedar Grove (USA) Japanese BioPlastics Association (Japan) Australasian BioPlastics Association (Australia & New Zealand) Consorzio Italiano Compostatori (Italy) SP Technical Research Institute (Sweden) Catalonian government (Catalonia, Spain)
Home compostability	Vinçotte (Belgium) DIN CERTCO (Germany) Australasian BioPlastics Association (Australia & New Zealand) Organics Recycling Group – Renewable Energy Association (UK)
Biodegradability in other environments	Vinçotte (Belgium) SP Technical Research Institute (Sweden)

*Note: There have been more certification bodies available for biodegradability since the original publication

Current standards that fall under these certification bodies include industrial ASTM D6400, ASTM D6868, NF-T 51-800, EN13432, EN14995, ISO17088, ISO18606, AS4736 and AS5810. In Europe, the predominant standards are NF-T 51-800, EN13432 and EN14995. In the United States, ASTM D6400 and ASTM D6868 are the preferred standards, while Canada adheres to CAN/BNQ 0017-088. Australia follows AS4736 and AS5810. In Brazil, the standard ABNT NBR 15448-2 is used. Additionally, there are global ISO standards, namely ISO17088 and ISO18606, although these are not as widely adopted.

To qualify for certification within these standards, biodegradation, disintegration, ecotoxicity and chemical characteristics of the product must be considered (TUV Austria, 2022), as described below:

Biodegradation

Testing must be completed within a maximum of 6 months for industrial composting and 12 months for home composting and must show at least 90% degradation. The total proportion of organic constituents that do not need to exhibit biodegradability should not exceed 5%. Until now, chemically unmodified packaging or natural materials were automatically accepted as being biodegradable without requiring testing. However, a recent update for ASTM D 6400-23 (Revised 6.3.3) states that ‘lignocellulosic substances are no longer exempted from biodegradation, but it can be demonstrated that they are “materials of natural origin” by showing >95% biobased content’.

Disintegration

The thickness tested must be clearly specified. According to test procedures outlined in ISO16929 or EN14045, within 12 weeks, fragments should be no larger than 2 millimetres (verified through sieving). Upon visual inspection of the compost material, no remaining product should be able to be visually distinguishable. If any components of the product are less than 0.1% dry weight, it does not need to be tested, provided this doesn't exceed 0.5% for the entire product.

Ecotoxicity

According to test procedures outlined in ISO16929 or EN14045, the concentration of testing material must be 10% on a wet mass basis. These tests make sure that there are no negative effects on germination and flora growth. ISO 17088 and AS4736 also include earthworm toxicity testing.

Chemical Characteristics

Heavy metal limits should not be exceeded as per the limit values specified in Table 2. Total fluorine levels are also considered in some of the standards. ASTM D6400, EN13432, AS4736 and AS5810 all include a 100ppm total fluorine limit. ASTM D6400 under BPI certification testing is specific to PFAS, whilst EN and AS standards consider fluorine concentrations (Ahlstrom – FluoroFree Products, 2023). It is important to note that naturally occurring fluorine in an inorganic filler like talc is non-toxic due to not being bioavailable, and thus, a product with >100ppm can be accepted with proof that the high concentration is due to the filler and not a different fluorinated chemical. PFAS content must also be self-declared using OECD guidelines (OECD Environment Directorate, 2021).

Table 2. *Heavy metal limits for different standards in different locations. (Deconinck & De Wilde, 2013)*

	Limit values (ppm on total solids)			
Metal	**Europe** EN13432*	**Australia** AS4736	**USA** ASTM D 6400**	**Canada** BNQ P 9011-911-5
Zn	150	150	1400	463
Cu	50	50	750	189
Ni	25	25	210	45
Cd	0.5	0.5	19.5	5
Pb	50	50	150	125
Hg	0.5	0.5	8.5	1
Cr	50	50	-	265
Mo	1	1	-	5
Se	0.75	0.75	50	4
As	5	5	20.5	19
F	100	100	-	-
Co	-	-	-	38

* EN13432 limits are identical to the ones prescribed to AS4736

** ISO17088/18606 refers to national/regional regulations dealing with metals

** Heavy metal content must be less than 50% of those prescribed for sludges/compost in the country where the product is sold

Table 3 summarises the criteria considered by various international standards for compostable products. Current standards do not test for additives apart from heavy metals and total fluorine. Considering Aotearoa New Zealand does not have its own standards, EN, AS or ISO 17088 standards appear to be most suitable as starting points for the regulations here. ASTM D6400, EN13432, AS4736/5810, ISO 17088 are all suitable for use in indicating composability; however, EN, AS, or ISO 17088 standards are preferable due to their more stringent heavy metal and TOF limits and more comprehensive ecotoxicity testing.

Table 3. *Comparative table of the relevant standards.*

Standard	EN13432	AS4736	AS5810	ASTM D 6400	ASTM D 6868	ISO 17088
Geographical Relevance	**Europe**	**Australia**	**Australia**	**United States**	**United States**	**Global**
Location of Composting	Specified on label	Industrial	Home	-	-	-
Biodegradation Testing Conditions	90% within 6 months	90% within 6 months	90% within 12 months	-	-	-
Heavy Metals Limit	Yes	Yes	Yes	Yes	Yes	Yes
TOF Limit (ppm)	100	100	100	100	-	100
Consideration for plastics	No	No	No	No	No	No
Consideration for BPA	No	No	No	No	No	No
Consideration for Phthalates	No	No	No	No	No	No
Ecotoxicity Testing Conditions	Terrestrial Plant (OECD 208 test method)	Terrestrial Plant (OECD 208 test method) & Earthworm (OECD 207 test method)	Terrestrial Plant (OECD 208 test method) & Earthworm (OECD 207 test method)	Terrestrial Plant (OECD 208 test method)	Terrestrial Plant (OECD 208 test method)	Terrestrial Plant (OECD 208 test method) & Earthworm (OECD 207 test method) Nitrification inhibition test for soil micro-organisms (optional).

5 Aotearoa New Zealand Specificity

5.1 Existing Policies/Guidelines/Regulations

The current composting landscape in Aotearoa New Zealand lacks specific policies, regulations or thought-out systems that allow for the effective widespread use and processing of compostable products. In Aotearoa New Zealand, there is a general reliance on international standards (e.g. AS4736 or EN13432) to provide trustworthy certifications for composting claims, but labelling or certification is not yet compulsory.

In the absence of regulations, different actors have published their own guidance/position statements on navigating compostability claims, e.g., the Ministry for the Environment's (MfE) Position Statement on compostable products (MfE, 2023). In 2018, The Parliamentary Commissioner for the Environment (PCE) provided concerned consumers with basic material outlining the EoL disposal options for common plastic products used in Aotearoa New Zealand (PCE, 2018). In 2019, WasteMINZ, a non-profit membership group supporting the waste and resource efficiency sector, issued a statement outlining its viewpoint on compostable products and providing recommendations regarding the advertising of these products (WasteMINZ, 2019). Key points in the statement included:

- Compostable products provide little to no value to compost; however, when food waste is a desirable input, this brings importance to making products in contact with food compostable.
- Products should provide end-of-life disposal information – specific terminology to describe under what conditions products are compostable.
- Products that risk compost quality, such as materials contaminated with biosolids or cleaning products, should not be made compostable.
- Compostable products should be designed in such a way that they do not devalue the compost.

The New Zealand Food and Grocery Council (FGC) established a sustainability subcommittee in 2019 and published a position statement in which they suggest that the current state of practice contains many flaws, such as customer confusion and a lack of mainstream standards, infrastructure and scale – they described their position on home composting as 'Not for Now' (FGC, 2020). It is acknowledged that home composting is particularly problematic as products consumed at home are often sent to landfills due to a lack of accessible facilities. Therefore, FGC recommended significant investment to improve collection and identification systems to allow for nationwide accessibility to facilities. Other stakeholders recommend smaller hubs that cater to 10,000 people rather than a centralised system, as they may be more efficient (FGC, 2020).

5.1.1 Communication and Labelling for Compostable Products

Environmental claims for compostable products encompass statements about a product's ecological impact throughout its lifecycle and efficient EoL disposal. To promote fairness, all businesses, regardless of size, must ensure accurate and supported environmental claims to avoid violating the Fair Trading Act 1986. Because some consumers value the environment in their purchasing decisions, this has led to the use of environmental claims as a competitive advantage by traders. While consumers demand truthful claims that are substantiated, they may lack the means to verify them. Reliable, certified information is crucial for confident purchasing decisions. Communication claims should be observed for both the advertising of the product and for the printed claims on the packaging. Guidelines relevant to the appropriate communication of compostable products have been published in Aotearoa New Zealand. For example, WasteMINZ issued a collection of resources to act as guidelines between 2019-2023 (WasteMINZ, 2022a), and the Commerce Commission published a report on environmental claims for traders (Commerce Commission New Zealand, 2020). There are no regulations in place to date.

A summary of the main guidelines related to communication of product compostability are:

- **Certification Logo and Number** – a certification logo must be displayed prominently, along with a unique certification number, indicating the product's compostable status.
- **Certification Database Link** – a direct link to the certification body's database should be provided in order to verify a product's compostability.
- **EoL and Degradation** – the expected EoL conditions and time frame for the degradation of the product should be clearly stated.
- **Materials and Supplier** – the names of materials used in the product should be specified, and a link to the supplier of the certified materials should be included, enhancing transparency.
- **Product Design** – the certification logo and appropriate end-of-life disposal methods (i.e. home or industrially compostable) should be prominently displayed on the product's packaging.
- **Non-Recyclable Status** – it is recommended to state if the product is non-recyclable on the packaging to avoid confusion and contamination of recycling streams.

- **Misleading Terms** – using vague or misleading terms like "plastic-free", "eco-friendly", or "biodegradable" should be avoided. Only the use of accurate and certified claims is acceptable.
- **Bio-based/Plant-based Claims** – the percentage breakdown of each component should be provided (e.g. 50% plant-based materials).
- **Avoid Mixing Compostable and Non-Compostable** – ensure that compostable and non-compostable materials, such as labels, are not mixed in the product.
- **No PFAS Intentionally Added** – customers may be assured that the product is free from intentionally added PFAS substances.

5.2 Existing Infrastructure & Marketplace

5.1.2 Infrastructure

Table 4 shows the current infrastructure available to process compostable products in Aotearoa New Zealand (WasteMINZ, 2022b).

Table 4. *Disposal Infrastructure in Aotearoa New Zealand (Adapted from WasteMINZ, 2022).*

Facility	Regions Served	Acceptance Criteria	Do Not Accept
Waipapa Landscape Supplies	Bay of Islands	'One off' compostable packaging from events	
Little & Brave Eco Nappies	Greater Auckland Metropolitan Area	All Little & Brave compostable products (bags, wipes and nappies) Certified commercially compostable disposal bags, gloves (EN13432, AS4736, ASTMD6400/68668)	• Non-compostable inorganic waste • Soft plastics • Polystyrene filler or foam • Food cling film • Cardboard • Home compostable products
The Compost Co. **(Community)**	Restaurants and cafes on Waiheke Island	Anything that falls under EN13432, ASTMD6400, or AS4736	• Non-compostable products or those containing non-compostable components • Bio-oxy-degradable products • Material contaminated with biosolids • Heatproof CPLA material

Facility	Regions Served	Acceptance Criteria	Do Not Accept
Envirofert Composting Facility	Auckland & Waikato	Composting materials that fall under certifications EN13432 or AS4736 and are made of: • Potato starch, corn starch, wood, wood pulp (e.g. cardboard packaging), poly lactic acids (e.g. plates, cutlery and cups), cutlery made of wood, bamboo or PLA	• Non-biodegradable plastic • Items with a plastic layer incorporated • Bio-oxy-degradable products • Material contaminated with biosolids
Xtreme Zero Waste* **(Community)**	Raglan	Composting materials must fall under certifications EN13432, AS4736, or ASMD6400	• Non-compostable products or those containing non-compostable components • Bio-oxy-degradable products • Material contaminated with biosolids
Revital – Cambridge	Central North Island – Waikato and Taranaki	Composting materials must fall under certifications EN13432, AS4736, or ASMD6400	
Palmerston North City Council (Awapuni Resource Recovery Park)	Palmerston North	Compostable packaging via its own food waste collection service and events recycling service only and must fall under certifications EN13432 or AS4736, including: • compostable coffee cups/bowls lined with PLA • food packaging products made from paper, cardboard, potato starch, sugarcane, pine, bagasse & bamboo materials • sandwich wraps & pouches made from vegetable wax coated paper • wooden (pine or bamboo) chopsticks, knives, forks, spoons & stirrers • Corn-starch compostable liners/bags (branding must use non-toxic inks, e.g. soy- based) • paper towels and napkins with no cleaning product on them	• PE/'wax' lined products • Oil-based plastics (including degradable plastic bags) • Material contaminated with human biosolids

Facility	Regions Served	Acceptance Criteria	Do Not Accept
Capital Compost - Wellington Southern Landfill	Wellington	Compostable packaging from approved waste companies and must fall under certifications EN13432, AS4736, or ASMTD6400/6868 Material acceptance criteria are the same as Palmerston North City Council	• All bioplastics • Corn-starch compostable waste bags • PE/'wax' lined products • Oil-based plastics (including degradable plastic bags) • Hard bamboo products • Material contaminated with human biosolids • Any other product claiming to be compostable but not clearly stating that it is made from the materials outlined
Greenwaste to Zero	Nelson/ Tasman	Composting materials must fall under certifications EN13432 or AS4736. Accept service ware.	• Food waste • Animal waste • Fats and oils • Material contaminated with human biosolids
Christchurch City Council Organics Processing Plant – Operated by Living Earth	Christchurch	Composting materials must fall under certifications EN13432 or AS4736 Made of wood or wood pulp or bagasse, e.g. cardboard packaging, cutlery made of wood or bamboo.	• Plastic (e.g. PLA) • Has plastic as a partial component • Labelled as bio-oxy-degradable plastic • Material contaminated with human biosolids
Timaru Eco Compost	Timaru District	• Material collected by kerbside organics bin collection and approved waste companies only • All food waste and garden materials • Animal droppings • Clean gib board offcuts, by arrangement • Dirty paper, hand towels, tissues, shredded paper and cardboard • Food-soiled paper products • Small animals/offal/hair/ nail	• 'Compostable' nappies • Ash • Bathroom and fireproof gib board/painted or nailed gib board • Cabbage trees and flax • Gravel and dirt/soil • Non-approved biobags/PLA packaging • Single-use coffee cups

*Not accepting waste at this time.

This list is in no way exhaustive, with home composting becoming increasingly popular. It is important to note, however, that the 'compostable' products that are subject to home composting rarely break down under these conditions (Gielen et al., 2022).

Comparing the facilities in Table 4, they all contain slight variations on what materials are accepted depending on certifications complied with and the composition of the waste itself. This can be due to a variety of reasons, including but not limited to:

- **Resource consents** – this dictates what materials are permitted to be processed, and as a result, sites such as green waste processing facilities are limited to materials found in gardens. Litter management is also required for resource consent and thus can restrict the acceptance of lightweight materials that can easily be transported via wind/water.
- **Fear of contamination** – the inability to identify the composition of products based on labelling alone can result in the introduction of contaminants and, thus, the potential for devalued compost.
- **Lack of clarity** – overall, it is often unclear what products are certified compostable as there are no enforced regulations in Aotearoa New Zealand. International labelling is therefore used.
- **Timeframe** – due to the different methods used at facilities, the length of time that the input material is processed and then added to the soil to compost varies. Consequently, certain materials may be unable to degrade within a desirable timeframe.

5.2.2 Commercially Available Compostable Products

In order to know what facilities and infrastructure is required to process compostable products in Aotearoa New Zealand, it is important to acknowledge and understand what materials are present in the marketplace. Different material types will have different temperatures, timeframe and microbe requirements, and thus, identifying the degree of heterogeneity in the marketplace is essential. While several companies in Aotearoa New Zealand manufacture compostable products, including Decent Packaging, Ecoware, Convex, Earthpac, Kiwi Packaging, etc., we can also expect a large proportion of compostable products to be imported.

The Packaging Forum 2020 (Renshaw, 2021) has identified examples of products that are currently in use in Aotearoa New Zealand. The list was separated into material categories, which include rigid/semi-rigid fibre, flexible fibre, flexible composite, rigid/semi-rigid composite, rigid polymer, and flexible polymer. The Packaging Forum also identified the different types of products within these categories and their compostability, and whether they are certified or just an assumed compostability based on similar products. While being an extremely useful source of information, the quantities of each product in the market and whether they end up in composting facilities (and which types) remain unknown. Unfortunately, the possible presence of additives to these products was not discussed by The Packaging Forum.

5.2.3 Commercially Available Testing Facilities

Scion's Biodegradation Testing Facility is the only DIN-CERTCO-accredited testing facility in Australasia that meets the required international standards/certifications for the complete compostability of products. DIN-CERTCO is a German certification organization specialising in assessing and certifying various products and services to conform to established standards and regulations. Compostability testing for accreditation purposes encompasses four stages: biodegradation, disintegration, ecotoxicity testing and chemical characterisation. As part of the chemical characterisation requirements, Scion tests for the products' total fluorine and heavy metal content (e.g. zinc, copper, nickel, cadmium, lead, mercury, chromium, molybdenum, selenium, and arsenic). These tests do not routinely include testing for phthalates or specific PFAS. It takes 18–24 months to undertake all four stages of compostability testing if this is required. Not all stages need to be performed for each test, depending on the information DIN-CERTCO already has about a particular test material. Under industrial composting conditions, testing the biodegradation stage will cost ~$15K, and ~$26K under home composting conditions. Detailed costs and future updates can be found on Scion's website.

Scion can test the biodegradability of additives such as glues and inks separately if required by the accreditation body DIN-CERTCO. Identification of specific chemicals other than those listed in the standards is not part of the routine compostability testing for accreditation purposes. Scion can test components of compostable products against a range of DIN- CERTCO Certification Schemes. They typically provide testing requirements for biodegradable and non-biodegradable additives. For example, non-biodegradable additives may be used but must not exceed 1% of the mass each and 5% of the total mass of the end product. Proven biodegradable additives may be used in quantities > 1% mass each.

Alternatively, products can obtain 'compostability reports' from commercial laboratories, such as the Hill Laboratory, which provide a nutritional and elemental breakdown of the product. These tests are usually inadequate for certification/compliance related to international standards on compostability. A comparatively short turnaround time, within a week instead of months, and substantially smaller cost (~$1K) make such tests attractive for interested businesses in this space.

Common chemical additives used in compostable products, such as PFAS and phthalates, can be tested in commercial laboratories in Aotearoa New Zealand, that specialise in advanced analysis. There are three laboratories that can undertake target analysis of more than 30 PFAS compounds: Eurofins, Analytica, and AsureQuality. The target analysis of PFAS costs ~$250/sample, while the non-target analysis, which provides comprehensive information on unknown PFAS additives, can cost up to $5K per sample. Eurofins has well-established methods for testing phthalates.

5.3 Socio-geographic Context

Aotearoa New Zealand has a current population of 5.2 million; however, with a land area of 268,021km², population density is low at 19 people per km² (Figure 4). The mountainous geography is a limiting factor, especially in the South Island. Although the South Island is larger in area, 77% of the population lives in the North Island, including 90% of the Māori population. The South Island is not only difficult to build infrastructure upon, but its economy is largely agricultural-based, which in turn contributes to the smaller people-to-land ratio.

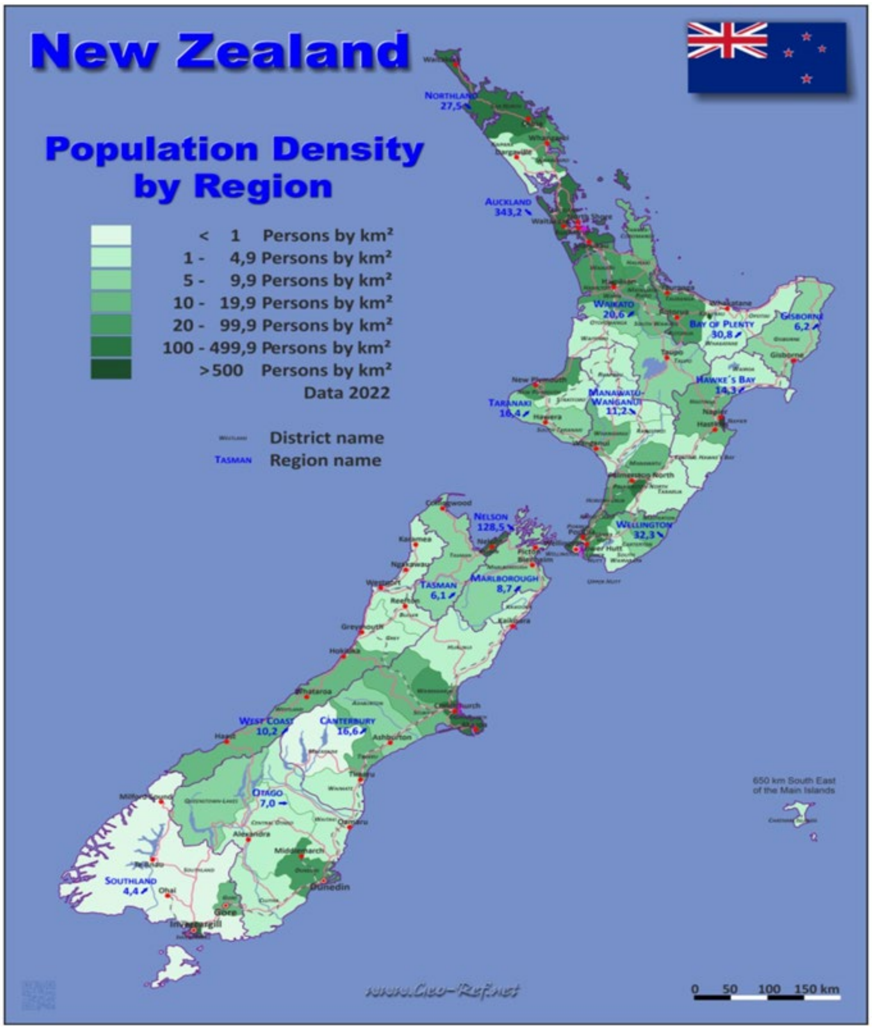

Figure 4. *Map of Aotearoa New Zealand showcasing population density (Map New Zealand, 2022)*

Because of the sparse distribution of the population in some regions, it is important to consider the accessibility different communities have to resources when implementing composting regulations and policies. The South Island has only three industrial composting facilities, which means people living long distances from these facilities may have difficulty in implementing potential composting solutions. An example is plastic recycling. Despite 1.76 billion plastic containers being used per annum in Aotearoa New Zealand, only 58% of people have access to kerbside recycling services, and thus large amounts of these materials are going to landfills (WasteMINZ, 2020).

It is also important to acknowledge Aotearoa New Zealand's capacity to provide solutions from a financial standpoint due to the low, spread-out population. Countries with higher GDP and a more dense population are able to establish more advanced infrastructure and waste management systems.

Therefore, solutions that work overseas may not be as effective if implemented in Aotearoa New Zealand.

5.4 Te Ao Māori

5.4.1 Unique Indigenous Worldviews Regarding Soil

"Te toto o te tangata, he kai, te oranga o te tangata, he whenua, he oneone"

"While food provides the blood in our veins, our health is drawn from the land and soils."

(Source: Te Ara)

"I have reverence for the soil because she is my tupuna (ancestor), and there is no separation between me as a human being and the soil as my ancestor."

(Hutchings et al., 2020)

Throughout history, Māori have developed extensive knowledge and values associated with the land and soil, which continue to hold authority and significance in present times (Harmsworth, 2022). Aotearoa New Zealand soils have played a crucial role in providing cultural, spiritual, social, emotional, and economic sustenance to them (Harmsworth, 2020; Hutchings et al., 2020).

Over the course of centuries, Māori have cultivated extensive resource management practices aimed at ensuring the sustainability, improvement, and preservation of the soil. In recent times, these practices have evolved to incorporate scientific advancements, technology, and innovation while still maintaining a strong foundation in traditional approaches and principles rooted in mātauranga Māori (Māori knowledge). Disregarding and misinterpreting indigenous knowledge in the context of ecological research, management, and policy in New Zealand can disrupt long-standing mātauranga and have negative impacts on the mana (authority) and well-being of Māori communities (Wehi & Lord, 2017).

Kawa

Kawa (Māori values and principles), rooted in traditional belief systems and encompassed within the broader Māori knowledge system (mātauranga Māori), play a significant role in how Māori understand, perceive, and interact with the environment (Marsden, 1988). Harmsworth (2022) has extensively explored the kawa that is integral to understanding soil health, which can be summarised as:

- Whakapapa (ancestral lineage)
- Mana (prestige and authority)
- Mauri (life force, vitality)
- Wairua (spiritual dimension)
- Taonga tuku iho (treasure passed down through generations)
- Maramataka (environmental/lunar calendar)
- Māra kai/māhinga kai (ability to provide healthy food)
- Tau utuutu (giving back what you take)
- Kaitiakitanga (environmental guardianship).

Kaitiakitanga

Māori connection to place is upheld through a practical philosophy of environmental stewardship known as kaitiakitanga. While kaitiakitanga is commonly understood as 'guardianship,' as emphasised by the Crown, local government, and some Māori individuals, it should also encompass the notion of 'resource management' (Kawharu, 2000); (Walker et al., 2019). The connection between indigenous communities and their environment is intricately woven into their narratives and cultural practices (Roberts et al., 1995; Sangha et al., 2019). Māori have fostered a deep and enduring bond with their land and the resources it provides for over 700 years. Recognising the significance of place allows for a more comprehensive approach to safeguarding the environment of a particular region (Kawharu, 2000).

Gaining an understanding of how indigenous values and practices, particularly kaitiakitanga, can be integrated into soil management holds the potential to preserve indigenous knowledge and provide a firm foundation for Māori identity (Walker et al., 2019). It is crucial to acknowledge that comprehending kaitiakitanga requires recognition of key concepts like mana (rangatiratanga) for 'authority,' mauri for 'spiritual life-principle,' tapu for 'sacredness, set apart,' rahui for 'prohibition or conservation,' manaaki for 'hospitality,' and tuku for 'transfer, gift, release' (Kawharu, 2000). The actions driven by kaitiakitanga stem from the creation narrative of Papatūānuku (earth mother) and Ranginui (sky father), establishing whakapapa between Māori and the natural environment (Mikaere, 2011).

Whakapapa

Whakapapa is a paradigm of 'genealogical layering,' where kaitiakitanga finds its reasoning. This paradigm organises all elements within the universe in linear (descent-time) and lateral (kinship-space) layers, serving as the fundamental basis for kaitiakitanga (Kawharu, 2000). Māori recognise the inseparable bond between themselves and the land, including the vital role of soils, through ancestral whakapapa. According to Māori mythology, Tāne, the deity of the forest, created the first woman, Hineahuone, from clay, symbolising the significance of soil and its connection to humanity (Hutchings et al., 2018)

Within the Māori worldview (Te Ao Māori), the condition of the soil directly influences human well-being (Stronge et al., 2020), and the understanding of soil health is approached holistically, blending cultural and scientific perspectives. In Te Reo Māori (the Māori language), the word 'whenua' signifies both 'land' and 'placenta.' As an example, the burial of the placenta at significant locations such as marae (meeting grounds) symbolises the profound spiritual and physical connection between land and people (Harmsworth & Awatere, 2013).

The well-being of the land is often used as an indicator of the people's health since both Māori and the environment share a connection through mauri and other forms of vital energy (Henare & Marsden, 1992; Timoti et al., 2017). The mauri of the soil is reflected in its capacity as a living ecosystem that sustains and supports all forms of life, including microbes, plants, animals, and humans (Hutchings et al., 2018).

Tikanga

The Māori approach to soil health highlights the tikanga (customs/protocols) and associated gardening practices of growing kai (food) (Hutchings et al., 2018). These practices seek to improve the mauri of the soil and include composting. In a personal conversation, Hineamaru Ropati (2023) shared examples of tikanga regarding composting:

- Compost natural elements such as organic waste, animal manure, seaweed, food scraps, straw, grass clippings, and plant remains.
- Avoid animal remains such as blood, meat or bone.
- Avoid human waste (e.g. soiled nappies) and human remains.
- Understand the precedence of anything you add to the compost (whakapapa). This also affects the moving of soil from one place to another.
- Using the māramataka to prepare the soil (compost) for high-energy periods that are good for planting.

Māori Decision Making of Soil Health Soil Security

The concept of soil security provides a comprehensive framework that aligns well with indigenous philosophy and thinking, offering a broader perspective for research, decision-making, policy, and management. Aotearoa New Zealand faces numerous soil-related challenges, currently framed predominantly around instrumental values, such as economic considerations, while giving limited attention to pluralistic values. On the other hand, indigenous approaches often exemplify a wider range of values, encompassing relational connectivity and intrinsic nature-based values alongside instrumental values (Hutchings et al., 2018; Hutchings et al., 2020; Stronge et al., 2020)).

The signing of the Treaty of Waitangi in 1840 between the British Crown and Māori tribes granted Māori recognised status and rights, which are now reflected in various policies and legislation (Harmsworth, 2022). Treaty agreements and settlements with iwi/hapū (tribal subgroups) have paved the way for co-governance and co-management roles, particularly in resource management (Ruru, 2018). Mana represents spiritual power, respect and autonomy and bestows upon Māori the authority to care for and protect the land and soil. Empowering hapū to take the lead in ecological restoration projects not only fosters engagement with the environment but also supports the preservation of biodiversity (Walker et al., 2019).

Pūtaiao

Pūtaiao is an exploration of the natural world from a scientific Te Ao Māori tirohanga (aspect or view), drawing from both Kaupapa Māori Theory (by Māori, with Māori and for Māori) and indigenous methodologies (Moko-Painting et al., 2023). Pūtaiao, as kaupapa Māori science, is firmly positioned in Te Ao Māori and informed by te reo, mātauranga, and tikanga. It is holistically interwoven by whakapapa and expressed through whanaungatanga (relationships, being in relation through whakapapa) as a way of approaching science (Moko-Painting et al., 2023).

Those connected to land and soil derive their information and knowledge from many sources. In most studies, the importance of soil information is stressed in food production and indigenous food security (Harmsworth, 2022). A number of tools informed by indigenous wisdom have been developed to support Māori decision-making of land and soils by understanding its basic capability, condition and opportunities at coarse scales (e.g. "Whenua viz", Harmsworth & McDowall 2011). To unlock the land's potential or to optimise decisions, several tools seek to overlay Māori land with various biophysical datasets, sometimes adding Māori cultural layers/sites (Harmsworth, 2022).

Harmsworth (2022) published a comprehensive list of soil health indicators from a Kaupapa Māori, a technical/non-technical and a science-based perspective. This is reproduced in Table 6.

Table 6. *Māori soil health indicators (Harmsworth, 2022).*

Kaupapa Māori soil assessments/indicators	**Farm, community – technical & non-technical assessments**	**Science based – including professional scientific, technical assessments, and science based (statistical) sampling strategies**
Kaupapa Māori based Mātauranga Māori knowledge based Based on Māori concepts and values *Approaches* (e.g.): Hua parakore (Māori organics) Kaitiaki assessments (pastoral, cropping, gardening, etc.) Farm KPIs Customary environmental indicators e.g. mahinga kai, mauri Cultural impact assessments Iwi/hapū/marae monitoring of contaminated sites Require in-depth Māori knowledge and understanding of particular environments and issues. Understanding of Māori values, goals, and aspirations. Kaupapa Māori approaches can include science and technical assessments. Examples: • Māori concepts, principles, and values • Kaupapa or mātauranga Māori based assessments and indicators • Traditional stories, narratives • Cultural heritage sites • Food, gardening and harvest practices (maara kai, mahinga kai)	*Examples:* • Can be subjective • Visual soil assessment (VSA) • Farm assessment • Farm indicators • Community based indicators (e.g. collectives) Can be subjective and practically based. Cost effective, relatively simple and short duration assessments linked to land management, soil management, farm operations, cropping, orchards, market gardens, hill country, etc. • Farmer, grower, orchardist, industry • Community values • Technical and non-technical assessments • School assessment programmes (soils and gardens) VSA pastoral, soil management guidelines, cropping, pastoral grazing, hill country *Indicators:* • Soil structure and consistence • Soil porosity	Scientific soil quality and soil health approaches: e.g., objective, measure 'soil quality' or a 'soil health target range' for each land-use *Example indicators measured –* Organic reserves • Total carbon • Total nitrogen • Mineralisable nitrogen Fertility • Olsen phosphorus Acidity • pH Physical status • Bulk density • Macroporosity Trace elements Contaminated soils Use science-based sampling strategy Science methods Laboratory analysis Require higher levels of technical input and skill, robust sampling strategies, analysis and interpretation, can be expensive and time-consuming.
• Maramataka (lunar calendars) • Soil management guidelines, best practice • Land management, whenua, kaitiakitanga Can include culturally based assessments for soil health and soil quality	• Soil colour • Earthworm counts • Compaction–tillage pan, clod development • Soil erosion • Organic matter • Plant indicators	

5.4.2 The Hua Parakore Framework as a Best-Practice Example

Hua Parakore is an indigenous verification and validation system for mahinga kai (food and product production) driven by the National Māori Organics Authority of Aotearoa New Zealand: Te Waka Kai Ora. The name of the framework comes from hua, meaning pure and para kore, which can be translated as unwanted contamination (H. Ropati, personal communication, 2023). The framework brings forth an interconnected and holistic approach to the production of food that connects to the cosmos with a focus on ecosystems, biodiversity, soil and human health (Te Waka Kai Ora, 2011).

The framework, according to Hutchings et al. (2018), is the result of research and development guided by Kaupapa Māori methodology. By incorporating Te Ao Māori this framework establishes specific tikanga for maintaining soil health and integrating Māori kaupapa into the New Zealand Standard for Organic Production NZSA 8410.2003 (Standards New Zealand, 2003). Moreover, Hua Parakore is a good example of a bi-cultural partnership through Treaty-based collaboration, having incorporated indigeneity into organic certification models (Hutchings et al., 2018).

The Hua Parakore framework encompasses six key kaupapa (principles) and a validation and verification process (Te Waka Kai Ora, 2011a, 2011b, 2011c, 2011d). Each kaupapa is briefly described in Figure 5. These kaupapa reflect the interconnected and holistic approach of the Hua Parakore framework.

Figure 5. *The Hua Parakore framework. (Te Waka Kai Ora, 2011)*

The Hua Parakore framework not only brings clarity to the concepts of food and soil sovereignty but also serves as a significant example of how Māori tikanga is applied to composting practices. To comply with The Hua Parakore framework, food producers must meet both the requirements of the New Zealand Organic Standard NZSA 8410.2003 and additional cultural requirements. As part of the verification process, soil is expected to be completely free of unsafe inputs. Producers are asked how they manage waste and other potential sources of contamination (such as waterborne contaminants or those derived from farming machinery) and may be asked to provide a soil test. Specific questions are also asked about composting practices and the use of livestock manure to enhance soil fertility (Hutchings et al., 2018).

5.5 Implications of a Te Ao Māori Approach to Soil Health

To achieve sustainable land management and soil security in composting, it is crucial to understand and incorporate pluralistic values that extend beyond instrumental and production-based values. Considering the deep cultural significance of soil in Te Ao Māori, strict measures should be applied to soil policy in Aotearoa New Zealand. Recognising the personhood of the soil as an ancestor, intimately linked to human physical and spiritual health, reinforces the need for comprehensive protection and management practices that prioritise the well-being of both soil and people. Whakapapa provides a foundation for understanding the relationships between humans, land, and soil ecosystems.

To ensure composting practices align with Māori values and knowledge, it is important to prioritise Māori-led and Māori-centred research on compostable products. This research should be conducted through a Pūtaiao lens, which combines Te Ao Māori and scientific approaches. Policy surrounding compostable products should be informed by the ethics and morals that underpin how research is conducted and how knowledge is used.

Social justice is to be observed during composting, as people have the right to know where their food comes from. It is crucial to enable autonomy and to respect mana for whakapapa-informed and place-based tikanga.

Centralisation of composting facilities undermines the capacity of Māori to know what will affect the integrity of their soil, as aptly expressed by Hineamaru Ropati: "When you do your own composting, you know what's in it" (personal communication, 2023). Moving soil from one location to another carries a risk of people not knowing what is in the soil. As an example, it is customary for Māori to bury a mother's placenta; this soil is therefore unfit for compost. Under this lens, home-based and marae-based compost should always be an option.

Mātauranga Māori can also play a vital role in interpreting tohu (environmental signs) for correct composting tikanga. For example, understanding the signs and indicators of the Māramataka phases can guide composting practices in accordance with Māori knowledge systems.

Finally, a fundamental aspect is to assess whether the current composting certification systems for compostable products align with Māori soil health indicators. The publication of soil health indicators by Harmsworth (2022), see Table 6, and The Hua Parakore framework (Te Waka Kai Ora, 2011) can provide guidance on the requirements that compost needs to meet in order to respect Treaty-based, bi-cultural standards.

In summary:

- Existing international certification systems for compostable products do not take into consideration Māori cultural requirements.
- Mātauranga Māori provides rich guidance on soil health indicators and other aspects that influence composting practices.
- We need further Aotearoa New Zealand-based, Māori-led and Māori-centred research on compostable products under a bi-cultural lens.
- Stricter measures should apply to the composting policy in Aotearoa New Zealand. Soil should be treated as an ancestor directly linked to physical and spiritual health.
- Social justice and the right to know the material origins of compost are undermined by the centralisation of composting facilities. Composting decisions should follow whakapapa-informed and place-based tikanga.

6 Key Findings and Compostable Packaging Framework

After a thorough literature review, consultations with key stakeholders, and consideration of Te Ao Māori, we present our key findings:

Labelling and claims

Reliable, certified information is crucial for confident purchasing decisions about compostable products. Communication claims should be observed for both the advertising of the product and for the printed claims on the packaging. Indicating a specific disposal route that is relevant to the local context is helpful. Unsubstantiated and/or misleading claims about products, e.g. 'eco-friendly' are an area of concern. Though guidelines are available, Aotearoa New Zealand currently has no regulations regarding labelling and product claims.

Additives in compostable products

There is currently a lack of data on the additives present in compostable products in Aotearoa New Zealand, which should be a priority for research. From a soil health perspective, with the available information about soil toxicity levels, regulations, and occurrence, PFAS and heavy metals appear to be of the highest concern among the harmful additives in compostable products. International certification schemes already include limits for heavy metals (see Section 4). We therefore recommend focusing more attention on potential soil health issues related to PFAS.

Aotearoa New Zealand-specific data

Data specific to the local context on the type and quantities of compostable products used, proportions expected to be composted in different compost streams, use of compost (application rates and frequency), and how those are likely to evolve in the future is unavailable. These data are essential to assess and minimise the potential impact of compostable products on soil health as the nature of the assessments undertaken to date is generally limited, only considering a few aspects of soil health. This review revealed that there is a lack of relevant Aotearoa New Zealand-specific research, including Māori-led and Māori-centred research on compostable products under a bi-cultural lens.

Defining Aotearoa New Zealand thresholds

Investigating the quantities and types of additives present in compostable products used in Aotearoa New Zealand, whether these are intentionally added by manufacturers or not, will be a starting point for defining threshold values. The focus should be on chemicals that are persistent, bioaccumulative and/or toxic, such as PFAS, due to their potential long-term effects. Avoiding the addition of persistent synthetic chemicals to soil is essential when considering Te Ao Māori. Data on the fate and impact of chemical additives are scarce globally, and it is thus not currently possible to recommend thresholds that are both achievable and will ensure no impact on soil health in the long term. Further scientific investigations and consultation with a range of stakeholders will be needed to define threshold values that are suitable to the Aotearoa New Zealand context.

Certification

Existing international certification systems for compostable products do not take into consideration Māori cultural requirements. In Aotearoa New Zealand, there is a general reliance on international standards (e.g., ISO17088, AS4736 or EN13432) to provide trustworthy certifications for composting claims, but as mentioned above, labelling is not yet compulsory. ASTM D6400, EN13432, AS4736/5810, ISO 17088 are all suitable for use in indicating composability; however, EN, AS, or ISO 17088 standards are preferable due to their more stringent heavy metal and TOF limits and comprehensive ecotoxicity testing. International regulations are evolving rapidly to address additives in compostable products, but they may not be suitable to fully address Aotearoa New Zealand's specificity.

Compostable Packaging Framework

We have developed a decision tree that translates our research findings into a practical framework. This draft framework offers guidance for businesses on best practices for preventing the contamination of compost with harmful chemicals that may negatively impact soil health (see below).

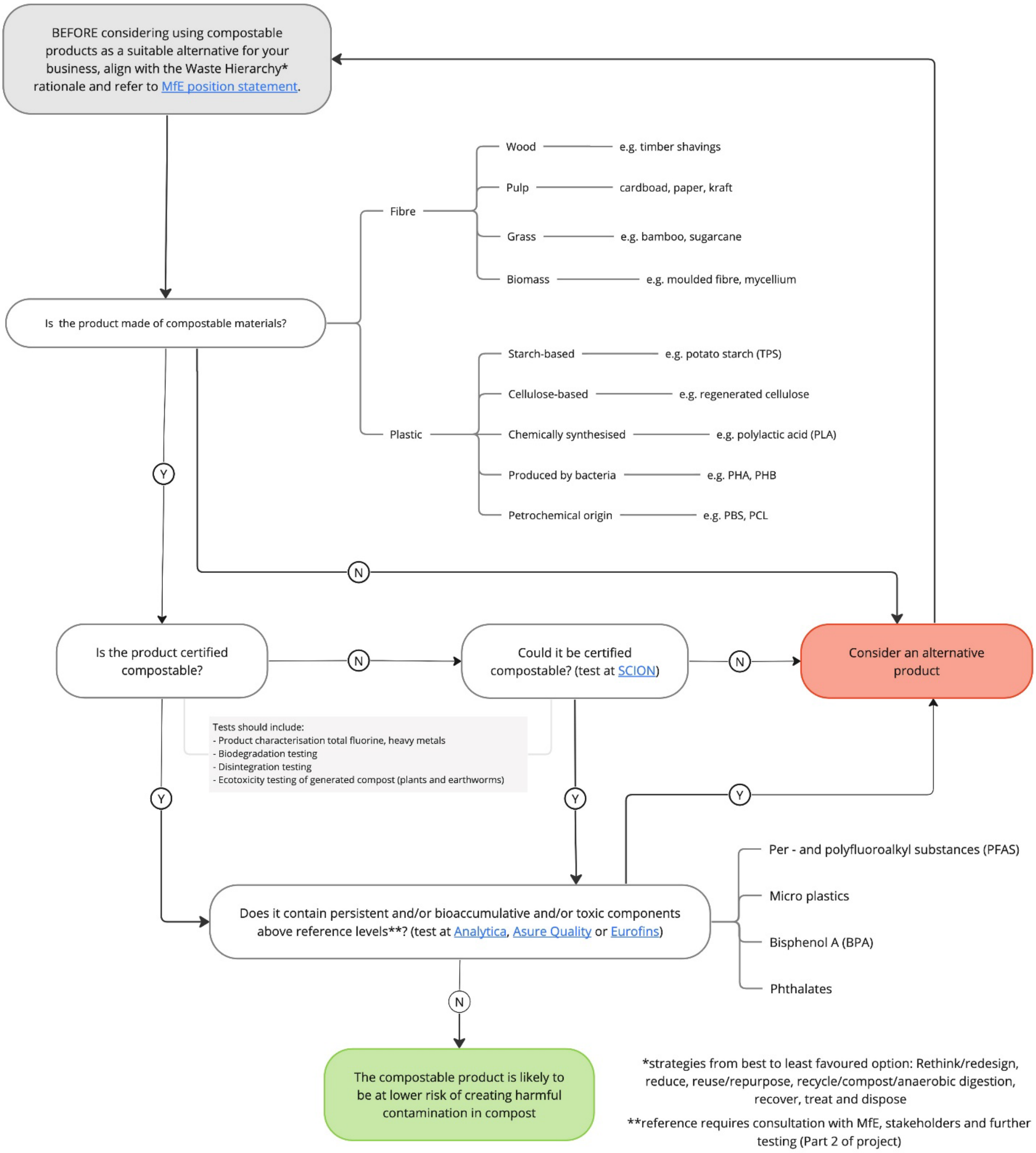

Figure 6. *The proposed draft framework.*

As shown in the draft framework (Figure 6), before considering the use of compostable products, businesses are asked to familiarise themselves with the Ministry for the Environment's (MfE) Position Statement on compostable products (MfE, 2023).

The draft framework provides a list of common compostable materials and suggests that products should meet at least one international standard. Such standards should include testing for ecotoxicity, disintegration, biodegradation, and product characterisation in terms of heavy metals and total fluorine. If the selected products are not certified, we recommend conducting the above-mentioned tests for certification.

Finally, we recommend testing all products for the levels of bioaccumulative or toxic components that may be present as additives. If the levels of these components are below established reference levels (to be determined in Part 2), the compostable product is unlikely to cause harmful contamination in compost.

7 Proposed Approach to Part 2

Investigations of compostable products and their possible soil eco-toxicity have been limited to date, leading to high uncertainties regarding the possible impact of compostable products on soil health. Full-scale investigations require large investments in terms of both time and budget, and they need to be well-targeted to generate information that can be used for decision-making. Our literature review indicates possible issues associated with the presence of additives in compostable products. It is currently unknown if this may be a real issue for Aotearoa New Zealand, and whether it requires a full-scale investigation.

For Part 2, we recommend conducting investigations addressing critical knowledge gaps relevant to Aotearoa New Zealand, to enable a strategic guide for future research needs. An initial screening phase will consider approximately ten compostable products, followed by more detailed investigations on two to four products. We propose the following steps:

1. Collect preliminary data specific to Aotearoa New Zealand, on the type and quantities of compostable products used, proportions expected to be composted in different compost streams, and use of compost (application rates and frequency).

2. Based on 1, select about ten products labelled as compostable or that may be perceived as compostable. The selection will cover a range of materials and functions (and thus potential additives).

3. Investigate the quantities and types of additives present in the selected products and whether these are intentionally added by manufacturers or not. The focus will be on substances that are persistent, bioaccumulative and/or toxic, such as PFAS and metals, but also bisphenols and phthalates.

4. For PFAS, we will consider different analytical approaches currently available at commercial testing laboratories (e.g. total fluorine, organic fluorine, targeted analysis) to support future regulatory recommendations for testing.

5. While the total content of additives is essential (i.e. full extraction), we will also assess the availability of the additives during and after the composting process (i.e. applying leaching tests before and after accelerated composting with a kitchen composter).

6. The data will be compared to international guidelines (PFAS and metals) to check for compliance with accreditations.

7. We will also determine the background concentration of additives in compost with minimal input of compostable packaging (e.g. food/garden waste only), which will provide essential information to establish future threshold values.

8. For a selection of two to four compostable products, we will screen toxicity to earthworms using the OECD guidelines (OECD 207).

9. We will also consult with Māori partners on soil testing approaches that would be culturally relevant in the future.

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Appendix

Table A1. *Summary of identified studies investigating the toxicity of compostable products and materials (after composting) under laboratory conditions (based on Williams, 2021)*

Product	Rate (%W/W)	Experimental Conditions	Degradation Parameters	Toxicity Assessment	Summary	Reference
HDPE Mater-Bi "Natural material"	~0.8% Mass loss	Batch reactor (9kg) Artificial compost Incubation for 12 weeks Incubation temperature 52-58°C Followed EN20200-2004	Mass loss	Seedling emergence (21 days) Sinapis alba (white mustard) Hordeum vulgare (barley) EN13432 (phytotoxicity)	93.5-99% (0% for HDPE) Seedling emergence 20-24% (in only 20% of containers) Reference compost not produced under the same conditions as treated compost	(Adamcová et al., 2019)
PVA + cellulose nanofiber blends	NS	Batch reactor Mature compost (150g) Incubation 150 d Incubation temperature up to 55°C ASTM D5338	Mineralisation (CO_2) Mass loss Visual (SEM) FTIR	Plant (cress and spinach) emergence/height/ mass, root length ASTM E1598 Final product mixed 50:50 with sterile soil	Up to 30% mineralisation of neat polymer; between 20-30% for blends. The glass transition temperature increased slightly over time, FTIR changed over time, and visual degradation was noted. Seed germination, height and root length increased for a higher percentage (up to 30%) of cellulose in the blend; compost control had poor germination (25-35%)	(Salehpour et al., 2018)
PLA film (0.02 mm)	2%	Batch reactor Garden soil/ compost (400g) Incubation 160 d Incubation temperature 30°C ASTM D5988	Mineralisation (CO_2) Thermal strength (DSC) Polymer length (GPC)	Soil nitrification ISO14238	The addition of lactate and Sphingobacterium + Pseudomonas aeruginosa sp inoculum increased mineralisation to ~25%; otherwise mineralisation ~10%. PLA had no effect on nitrification	(Satti et al, 2018)

Product	Rate (%W/W)	Experimental Conditions	Degradation Parameters	Toxicity Assessment	Summary	Reference
PLA Polyester urethane (0.10.6 mm)	17%	Batch reactor (5L) Mature compost Incubation 200 d Incubation temperature 58°C	Mineralisation	Bioluminescence assay (Vibrio fischeri) Plant growth; cress (Lepidium sativum), radish (Raphanus sativus), barley (Hordeum vulgare) OECD 208	Mineralisation of PLA ~90% after 200 d Bioluminescence assay included 11 biodegradation intermediates and additives, including lactic acid, lactide, succinic acid and 1,4-butanediol; EC50 greater than 3g/L for all components except for stannous octoate (0.1-0.6 g/L), 1,6 hexamethylene diisocyanate (0.02-0.1 < g/L) and 1,4 butane diisocyanate (0.02-0.2 < g/L).	(Tuominen et al., 2002)
PLA cutlery PLA/paper Cellulose film	1-2%	Batch reactor (0.25L) Mature compost Incubation for 29 days Incubation temperature 60ºC	Mineralisation (CO2)	Microbial community	Disintegration extent ~100% aerobic (minimal for anaerobic). High plastic treatment (2% w/w) had a significant increase in bacterial/fungal abundance.	(Zhang et al., 2017)

Table A2. *Summary of identified studies investigating the toxicity of compostable products and materials (after composting) under field conditions (based on Williams, 2021)*

Product	Rate (%W/W)	Experimental Conditions	Degradation Parameters	Toxicity Assessment	Summary	Reference
PLA plate PLA cutlery	NS	Incubated for 130 d, Windrow (turned) GO waste	Mass loss	Phytotoxicity (10 d) Lycopersicon (tomato) ISO11269 (seedling emergence)	100% degradation after 130 days for all PLA material. Germination is low (27%) compared with compost (50%); exposure conditions not clear for seedling emergence test	(Greene, 2007)
PLA fibres	0.1-5%	Tunnel pasteurisation (2 weeks) Windrow (13 weeks)	Visual	Earthworm (14-60 d); mortality, burrowing, growth, reproduction) Wheat (60 d); growth, yield, mortality	PLA was not degraded prior to ecotoxicity testing (added to compost). Earthworm mortality 8-17% in some treatments, and reduction in biomass 2-17% occurred in all treatments (including controls and not dose-dependent). No significant effects for all wheat endpoints assessed. No significant effects on compost physicochemical parameters	(Huerta-Lwanga et al., 2021)
PET PBAT PBS PHA PLA EVOH PP (20 mm)	NS	Incubated for 450 d Static pile compost Ambient conditions	Mass loss	Microbial DNA abundance/ diversity	PBS, PHA ~5-8% mass loss (no loss for others); ambient conditions ineffective for degrading these polymers Highest DNA abundance for PBS and PHA	(Mercier et al., 2017)
PLA PLA/blend Fibre Ground	10-20% (isolated in bags)	Incubation for 45-82 d, Windrow, aerated static pile, anaerobic digestion	Mass loss	Microbial activity and community (PLFA)	Disintegration extent ~100% aerobic (minimal for anaerobic digestion). High plastic treatment had a significant increase in bacterial/fungal abundance.	(Zhang et al., 2017)

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