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Additives in Compostable Products in Aotearoa New Zealand

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For:

The Ministry for the Environment
Manatū Mō Te Taiao

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Contents

List of Abbreviations

Acronym	Explanation
PFAS	per- and polyfluoroalkyl substances
BPA	bisphenol A
CIC	combustion ion chromatography
TF	total fluorine
TA	target-analysis
NTA	non-target analysis
TOP	total oxidisable precursors
QToF- LC/MS	quadrupole time-of-flight - liquid chromatography/mass spectrometry
m/z	mass-to-charge ratio
PFPrA	perfluoropropionic acid
PFBA	perfluorobutanoic acid
PFPeA	perfluoropentanoic acid
PFHxA	perfluorohexanoic acid
PFHpA	perfluoroheptanoic acid
6:2 FTUCA	6:2 fluorotelomer unsaturated carboxylic acid
6:2 FTCA	6:2 fluorotelomer carboxylic acid
Branched_PFOA	branched perfluorooctanoic Acid
PFOA	perfluorooctanoic Acid
5:3 FTCA	5:3 fluorotelomer carboxylic acid
6:2 FTOH	fluorotelemor alcohol
TFSI	bis(trifluoromethane sulfonyl)imide
NVHOS	2-(1,2,2,2-tetrafluoroethoxy)perfluoroethanesulfonic acid
GenX	perfluoro(2-propoxypropanoate)
ADONA	4,8-dioxa-3H-perfluorononanoic acid
PFOS	perfluorooctane sulfonate
NIAS	non-intentionally added substance
HSNO	hazardous substances and new organisms
PNEMP	PFAS National Environmental Management Plan
FCM	food contact material
LOD	limit of detection

Acronym	Explanation
SCS	Soil Contaminant Standards
EGA	evolved gas analysis
TBBPA	tetrabromobisphenol A
DMP	dimethyl phthalate
DEP	diethyl phthalate
DIP	diisopropyl phthalate
DBP	dibutyl phthalate
DIBP	diisobutyl phthalate
DNPP	di-n-pentyl phthalate
DHXP	di-n-hexyl phthalate
DHP	di-n-heptyl phthalate
DNOP	di-n-octyl phthalate
DINP	diisononyl phthalate
DDP	diisodecyl phthalate
DIDP	diisodecyl phthalate
BBP	benzyl butyl phthalate
DEHA	di(2-ethylhexyl) adipate
DEHP	di(2-ethylhexyl) phthalate

Executive Summary

The report presents the findings of an analysis of selected compostable products in Aotearoa New Zealand, focusing on the effects of additives on soil health. Ten products were selected to test for PFAS, heavy metals, polymers, phthalates and bisphenols before being screened for their potential ecotoxicity implications in soils. The amount and types of additives in the products varied greatly, with standout results showing high PFAS content in a fibre tray and the presence of nearly all tested additives in a pizza box. Ecotoxicity tests conducted on a select few products also indicated that more work is needed to understand how the additives affect the cycling of nutrients in the soil and, therefore, its health. The results of this report will help inform future policy related to compostable products whilst generating new knowledge that can support the decisions of practitioners (manufacturers, users, composters) and guide future research priorities.

1 Part One Overview

An extensive literature review of compostable products globally and in Aotearoa New Zealand was conducted in Part One of this project. The key findings summarised below guided further investigations into the presence of additives in compostable products presented in this report.

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.

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, per- and poly-fluoroalkyl substances (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 3.2). 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. There is a lack of relevant Aotearoa New Zealand-specific research, including Māori-led and Māori-centred research and practices 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, and 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 total fluorine (TF) 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.

Part Two of the project aims to provide insights into improving regulations and practices related to compostable products in Aotearoa New Zealand, with a focus on soil health and cultural relevance. It comprised testing ten carefully selected compostable products for PFAS, heavy metals, polymers, phthalates, and bisphenols.

This report presents the findings from testing these additives, along with ecotoxicity assessment screening of the selected compostable products, and provides key take-home messages.

2 Product Selection Criteria

In consideration of the project's budget and timeframe limitations, ten products were chosen for testing. The selection of these products was based on a set of criteria outlined below:

Labelling related to Compostability

There are a variety of certifications and labelling associated with products on the market. This can range from full certification, labelled with claims of compostability, and products with no labelling yet perceived as compostable. Thus, it is important to capture a variety of these labels to encompass potential differences.

Previous Research

Research in the compostable products sector is expanding, necessitating a re-examination of product categories previously investigated overseas to obtain comparative data within Aotearoa New Zealand. This effort aims to enhance our comprehension of our global standing. Equally crucial is the selection of product categories with limited existing data to ensure that the research contributes to knowledge creation in the field.

Product Abundance

Aotearoa New Zealand offers a range of compostable products with varying levels of popularity in the market. When selecting products for additive screening, it is important to choose those that align with the products commonly used by consumers and that are likely to be encountered at composting facilities.

Product Composition

A wide array of compostable product compositions exists, with fibre-based materials being the most commonly utilised in Aotearoa New Zealand (Ministry for the Environment, 2022). Fibre-based products can be derived from materials such as wood, pulp, grass, and biomass. Polymer-based products, on the other hand, can be starch-based, cellulose-based, chemically synthesised, produced by bacteria, or derived from petrochemicals. It is crucial to include a wide range of these compositions in the study, as their diverse makeup involves various additives.

Links to Policy

Given the recent implementation of the new food scraps bin programme in Auckland, Aotearoa New Zealand, this project places special emphasis on screening products that are currently used or could potentially be used in conjunction with this initiative. The nationwide bans on certain single-use and hard-to-recycle plastics in 2022 and 2023 underscore the importance of exploring environmental alternatives that are safer for the environment of Aotearoa New Zealand (Ministry for the Environment, 2022).

Multiple Uses

Choosing multifunctional products enables more efficient use of analytical techniques to scan for additives used for functional improvements.

Based on these criteria, ten products were selected for testing (Table 1). These products were sourced from a variety of locations, from a local café to the local supermarket.

Table 1. Compostable products selected for the testing of additives.

Item No.	Item	Primary Composition	Labelling
1	Aqueous-coating Paper Cup	Paper with plant-based bioplastic	Certified AS5810, AS4736, EN13432
2	PLA Cold Cup	PLA	Certified AS4736 & EN13432
3	PLA-lined Paper Cup	Paper with PLA lining	Certified ASTMD6400, ASTMD6868
4	Compostable Tea Bag	Unbleached filter paper, cotton string, paper tags	Certified AS5810
5	Bin Liner	Cornstarch-derived	Certified (Home, & Industrial), AS5810, AS4736
6	Flat Brown Paper Bags	Kraft paper	Assumed compostable
7	Newspaper	Paper	Assumed compostable / Used as an alternative to bin liners
8	Cardboard Pizza Box	Corrugated cardboard, sometimes recycled	Mixed knowledge on recycling/compostable
9	Wooden Cutlery	Magnolia wood	Assumed compostable
10	Unlined Fibre Tray	Sugarcane	Not certified, suggested compostability ('please compost label'), declared added PFAS

3 Additive Testing

This section presents the results of testing the ten compostable products selected. The additives discussed are per- and polyfluorinated substances (PFAS), heavy metals, polymers, phthalates and bisphenols. For each type of additive, the results are presented and discussed after a brief summary of their key characteristics and a description of the analytical methods.

3.1 PFAS

Introduction

PFAS are synthetic chemicals characterised by their robust carbon-fluorine bonds that provide the advantageous qualities of heat stability, resistance to degradation, and repulsion of water and grease. These qualities are particularly desirable for food-contact materials. This was highlighted as a concern in the first report due to their incredible stability in the environment and their effects on soil quality.

Methods

Multiple methods are used here to determine the presence of PFAS. Initial screening for PFAS involved combustion ion chromatography (CIC) to analyse total fluorine (TF) content. Whilst the method cannot specify what specific PFAS are present in the sample, it serves as a good indicator of the potential total mass of PFAS.

To further understand how this fluorine relates to specific PFAS, target analysis (TA), non-target analysis (NTA), and total oxidisable precursor (TOP) assay were also used. An NTA using the quadrupole time of flight liquid chromatography-mass spectrometry (QToF-LC/MS) method helps to identify the m/z of unknown PFAS and, thus, allows identification of their chemical structure. A TA involves the use of reference materials to measure for specific PFAS. Results for NTA are typically reported as a percentage of the m/z peak area relative to the largest peak signal in the sample. This method of reporting results from the lack of analytical standards for PFAS due to the extensive list of compounds under this group. The TOP assay approach is based on the complete oxidation of PFAS precursors to understand the relative quantity of precursors that have the potential to form PFAS. These methods are complementary and provide a wider characterisation of the PFAS found within the compostable products.

Results

Detectable levels of TF were found in six out of ten products tested (Table 2), with the unlined fibre tray exceeding 100 mg/kg. Often, a value of 100 mg/kg TF is associated with a threshold of 'intentional addition' (The Packaging Forum, 2022). The limit of detection for the TF analysis was 5 mg/kg.

Table 2. Results of TF analysis using CIC and NTA using QTof-LC/MS to analyse compostable products. The value in bold exceeds 100 mg/kg, which is the limit for compostable certification. N/A under NTA shows the product did not undergo this analysis technique.

Item (Item Number)	TF (mg/kg)	NTA
Aqueous-coated Paper Cup (1)	6.2	-
PLA Cold Cup (2)	< 5	N/A
PLA-lined Paper Cup (3)	29	-
Compostable Tea Bag (4)	15	-
Bin Liner (5)	< 5	N/A
Flat Brown Paper Bag (6)	14	-
Newspaper (7)	< 5	N/A
Cardboard Pizza Box (8)	15	-
Wooden Cutlery (9)	< 5	N/A
Unlined Fibre Tray (10)	**810**	**PFPrA, PFBA, PFPeA, PFHxA, PFHpA, PFOA, 5:3 FTCA, PFMeS, TFSI, NVHOS, 6:2 FTUCA, 6:2 FTA, 6:2 FTOH**

Samples with TF levels above the detection limit were analysed for NTA. In five of the six samples analysed for NTA, no PFAS were detected. Only the item that exceeded the TF threshold (unlined fibre tray) contained a range of PFAS (Table 2), indicating the likelihood of intentional additions.

We hypothesise that these compounds may be highly polymeric PFAS that are currently beyond our analytical capabilities, or they could be substances not represented in any of the instrument's existing libraries. This underscores the possibility that the industry may be incorporating fluorinated substances that are not yet well-understood or recognised.

The analysis of the unlined fibre tray yielded intriguing results, including the identification of perfluorooctanoic acid (PFOA), which is listed in the Stockholm Convention on Persistent Organic Pollutants. The results also showed hexafluoropropylene oxide dimer acid (6:2 FTOH) and its breakdown products hexafluoropropylene oxide tricarboxylic acid (6:2

FTCA), hexafluoropropylene oxide monocarboxylic acid (6:2 FTUCA), perfluorohexanoic acid (PFHxA), perfluoropentanoic acid (PFPeA), perfluorobutanoic acid (PFBA), and perfluoropropanoic acid (PFPrA). These are likely coming from the breakdown of a fluoropolymer, which contributed significantly to the 810 mg of TF. PFOA returned the highest peak (Table 3), alluding to its abundance in the product.

5:3 FTCA is a compound often found in leachate from landfills and originating from PFAS precursors in textiles and food packaging. Of particular interest is the detection of bis(trifluoromethane sulfonyl)imide (TFSI), which occurs as lithium salt and is commonly used as an electrolyte in lithium-ion batteries. (Rensmo et al., 2023). Another intriguing compound detected in the NTA analysis is 2-(1,2,2,2-tetrafluoroethoxy) perfluoroethanesulfonic acid (NVHOS). NVHOS serves as an analogous processing aid or raw material for the production of perfluoroalkyl sulfonate-based products, similar to other ether-based PFAS species such as GenX (perfluoro(2-propoxypropanoate)) or ADONA (4,8-dioxa-3H-perfluorononanoic acid).

Table 3. NTA results for Unlined Fibre Tray with most prominent PFAS.

Compounds	Peak Area (%)
PFOA	100
6:2 FTUCA	37.53
PFHxA	33.91
PFPrA	23.44
Branched_PFOA	10.99
PFBA	9.76
PFHpA	4.47
PFPeA	3.12
6:2 FTCA	1.05
6:2 FTOH	0.55
5:3 FTCA	0.31

Because of the return of a high PFOA reading, a TOP assay and target analysis were also conducted on this product, which confirmed the presence of PFOA and PFHxA.

Discussion

Comparing the TF values to the literature, the unlined fibre tray (TF=810 mg/kg) is in line with previous reports, with one study reporting ranges from 660-1200 mg/kg (Mindy O'Brien & Angela Ruttledge, 2021), 6.5-12 times the 100 mg/kg limit set for certifications (see next section). Brown paper bags often contain relatively high levels of intentionally added PFAS (220-800 mg/kg) (Straková et al., 2021). Pizza boxes have shown mixed results in the literature, with one study showing many samples from the United Kingdom, the Netherlands and

Germany having no PFAS treatment (<100 mg/kg) but still present at detectable levels (Straková et al., 2021).

The tea bag sample tested in this study was bought with tea leaves inside, and those were removed prior to analysis. Previous studies on tea products have uncovered the presence of short-chain PFAS in teas sourced from China. Additionally, research suggests that the type or variety of tea impacts the occurrence of PFAS in these products (Jala et al., 2023). Tea bags, on the other hand, have not been studied extensively. One study examined tea bags from India and found that the majority of samples contained PFOS at concentrations ranging from the limit of quantification to up to 0.3 mg/kg (Jala et al., 2023).

Paper cups vary in PFAS content due to the varying compositions, with a few studies indicating less than 1 mg detected (Chen et al., 2024; Kit Granby & Julie Tesdal Håland, 2018). Overall, the PFAS results of the ten products tested were comparable to those reported in other studies.

Regulations/Certifications/Standards

PFAS levels in compostable products that exceed 100 mg/kg are typically considered to be intentionally added by manufacturers, as reflected by certifications (The Packaging Forum, 2022). Values below 100 mg/kg can be regarded as non-intentionally added substances (NIAS) and often are a result of PFAS being present in the starting materials or contamination during the manufacturing process. The unlined fibre tray is the only product with PFAS levels greater than 100 mg/kg (namely 810 mg/kg). This indicated the intentional addition of PFAS, which prompted further investigation.

The US Environmental Protection Agency has recently announced a new enforceable drinking water standard for PFAS, restricting the maximum contaminant levels to 4 parts per trillion for PFOA, PFOS and ten parts per trillion for PFHxS, GenX and perfluorononanoic acid (PFNA) (US EPA, 2024). Although not directly related to soil health, this serves as an indicator of the perceived toxicity of these chemicals at such low concentrations.

In Aotearoa New Zealand, PFOA and PFOA-related compounds are restricted by the HSNO Act due to them being classified as persistent organic pollutants under the Stockholm Convention and thus should not be present in any products (New Zealand Legislation, 2004). While the unlined fibre tray contains PFOA, the concentrations need to be confirmed to apply the HSNO Act. This product, therefore, warrants further investigation outside the scope of this work.

The Ministry for the Environment has also released some human health-based guideline values for PFOA/PFOS in soil, which are consistent with those listed in the PFAS National Environmental Management Plan (PNEMP) (Ministry for the Environment, 2018). These range from 0.1-50 mg/kg for PFOA and 0.009-20 mg/kg for PFOS/PFHxS, depending on the land use. Although this is in regard to human health and not soil health, it highlights values that are deemed acceptable in the environment.

Soil

The PFOA detected in the unlined fibre tray does not degrade during the composting process and, therefore, is a concern for soil health. The compound PFOA has detrimental effects on earthworms (weight loss) at concentrations greater than 25 mg/kg soil (He et al., 2016). Other fluorotelomer polymers present in these samples also have the ability to break down into PFOA (Washington et al., 2009). Furthermore, biodiversity and connectivity of soil bacteria could be reduced with PFAS levels greater than 0.1 mg/kg soil (Cao et al., 2022). This indicates that the levels of PFAS found in these products have the potential to disrupt soil ecosystems if the compost is contaminated with similar levels of PFAS present in these products. In relation to compost, it is also expected that the PFAS found in these products will contaminate any compost intended for application to soil, with many studies highlighting the relationship between food contact material's (FCM) breakdown and PFAS-ridden compost (Goossen et al., 2023; Timshina et al., 2024).

3.2 Heavy Metals

Introduction

Heavy metals are found in compostable products for several reasons. They may be present in the raw materials, such as recycled materials, or intentionally added for colouring to enhance the products' aesthetics. Inadequate quality control during the manufacturing process can also lead to the introduction of heavy metals into the products.

Methods

Heavy metals were analysed after microwave-assisted digestion. Approximately 200 mg of product was digested using nitric acid and hydrochloric acid (5:1 volume ratio) to dissolve all organic components of the sample whilst stabilising metals suspended in solution. The metals were then analysed using inductively coupled plasma mass spectrometry (ICP-MS). Argon was used to create the plasma that ionises the molecules in the sample extract before they are separated by m/z ratio and thus characterised.

Results

Table 4 presents heavy metals involved in the certification of compostable products. The hyphen represents where values were below the limit of detection (LOD). The LOD is the lowest value in which a concentration can be reported due to the sensitivity of the analytical method used. It should be noted that a metal may still be present in the sample at concentrations below the LOD. Furthermore, the detection limit for Se was greater than the maximum allowable concentration for certification of compostable products. The metals As, Se, Mo, Hg and Cd were not detected at the LOD level for the ten products analysed in this report, while Cu in the newspaper and in the Cardboard pizza box were above the maximum allowable levels. All the other analysed elements are not considered in the certification of compostable products, and hence, the following discussion is limited to elements listed in Table 4.

Table 4. Heavy metal analysis of compostable products in mg/kg (Bold values refer to levels above certification limits).

	Item #1	Item #2	Item #3	Item #4	Item #5	Item #6	Item #7	Item #8	Item #9	Item #10	LOD
As	-	-	-	-	-	-	-	-	-	-	1.34
Cd	-	-	-	-	-	-	-	-	-	-	0.05
Co	0.0	-	-	0.2	0.1	0.5	0.1	0.5	0.1	-	0.03
Cr	1.5	-	0.8	0.8	0.8	3.7	0.8	3.4	-	1.1	0.54
Cu	29.9	2.3	11.3	4.9	3.4	11.8	**70.7**	**80.5**	2.4	1.3	0.70
Hg	-	-	-	-	-	-	-	-	-	-	0.27
Mo	-	-	-	-	-	-	-	-	-	-	0.54
Ni	1.1	-	-	2.3	0.7	2.0	0.7	1.2	-	-	0.54
Pb	0.8	-	-	4.8	0.4	8.8	3.2	3.7	0.7	0.5	0.13
Se	-	-	-	-	-	-	-	-	-	-	2.68
Zn	-	-	-	22.2	28.6	24.3	14.2	34.6	8.7	10.9	8.04

Item#1 - Aqueous-coated Paper Cup, Item#2 - PLA Cold Cup, Item#3 - PLA-lined Paper Cup, Item#4 - Compostable Tea Bag, Item#5 - Bin Liner, Item#6 - Flat Brown Paper Bag, Item#7 - Newspaper, Item#8 - Cardboard Pizza Box, Item#9 - Wooden Cutlery, Item#10 - Unlined Fibre Tray; LOD - Limit of Detection

Discussion

Markowicz & Szymańska-Pulikowska (2019), prior to composting, found that all compostable bioplastics they investigated contained Cu, Zn, Pb, Cr, Ni and Cd, with Cu and Zn showing the highest values. Furthermore, they found that certified compostable bioplastic-based products could contain a variable range of heavy metals from 40 to 300 mg/kg (Markowicz & Szymańska-Pulikowska, 2019).

The heavy metal content in newspapers can vary depending on the location of sampling because font thickness, colour and photos can carry different amounts of heavy metal content compared to plain paper (Ahmed et al., 2022). For example, Cd was measured in light fonts in the range of 0.54-3.55 µg/kg, in bold fonts in the range of 0.88-13.42 µg/kg and in pictures in the range of 1.17-5.59 µg/kg (Ahmed et al., 2022). No Cd was detected in our newspaper product, despite our sample including a partially printed area. In paper bags, Skrzydlewska et al. (2003) determined Cr (0.25-0.5 mg/kg) and Pb (0.28-0.35 mg/kg) at values lower than in this study. In moulded fibre tableware, Liu et al. (2020) determined Pb levels of 0.36 mg/kg and As levels below the detection. This was comparable to the findings in our study. The levels of Pb, Ni and Cu measured in our pizza box were also lower than similar products reported by Sood & Sharma (2019).

Regulations/Certifications/Standards

Table 5 shows the limits of heavy metals relevant to compostable standards in Europe, Australia, the USA, and Canada. Newspaper and the Pizza Box (both uncertified) exceeded the maximum limits for certification for Cu. These elevated Cu levels could likely be attributed to the pigment/ink used in the products. The presence of Pb and Cr in multiple products could also become of concern in the scenario where large quantities of compostable products reach compost streams.

Table 5. Heavy metal limits for different standards in different locations. (Deconinck & De Wilde, 2013)

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

* 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

Soil

Excessive concentrations of heavy metals (As, Cd, Cr, Hg, Pb, Cu, Zn, Ni, in particular) are known to have negative impacts on soil organisms, bacterial diversity, and plant growth. Metals do not degrade, and the repetitive application of contaminated compost made of compostable products may eventually lead to accumulation to levels that are detrimental to soil Health. Metal Cd is generally of concern mainly due to plant intake and human consumption. The absence of Cd in the products tested in this study is encouraging as this metal, in particular, can retard the growth and development of crops (Haider et al., 2021).

Table 6 shows Manaaki Whenua's Soil Standards for different land-use scenarios; Cu has been restricted in other jurisdictions, such as the European Union, to avoid its accumulation to excessive levels in the soil. Although there is currently no standard value in Aotearoa New Zealand for Cu in soil, the guideline value is 100 mg/kg (Manaaki Whenua, 2019). All metal concentrations tested for these products were below the guideline values for the beneficial use of organic materials on productive land in Aotearoa New Zealand (Fietje et al., 2017).

Table 6. Summary of soil contaminant standards – SCSs (health) – for inorganic substances (mg/kg)

Land-use scenario	As	B	Cd	Cr (VI)	Cu*	Pb	Hg
Rural residential/ lifestyle block 25% produce	17	NL	0.8	290	NL	160	200
Residential 10% produce	20	NL	3	460	NL	210	310
High-density residential	45	NL	230	1,500	NL	500	1,000
Recreation	80	NL	400	2,700	NL	880	1,800
Commercial/ industrial outdoor worker	70	NL	1,300	6,300	NL	3,300	4,200
*Soil guideline value for Cu is 100 mg/kg (Manaaki Whenua, 2019)							

3.3 Polymers

Introduction

It is crucial to comprehend the polymer makeup of compostable items to gauge the risk of potential microplastic/nanoplastic pollution in the environment. This was achieved here using an advanced analytical approach, pyrolysis-gas chromatography/mass spectrometry (Pyr-GC/MS), where a sample is decomposed at elevated temperatures to characterise the fragments generated.

Methods

Initially, an evolved gas analysis (EGA) was conducted to determine the temperature at which the product should be heated and to determine if there were any major differences between various parts of the product (e.g., ink vs. non-ink). This technique involves heating a sample to high temperatures to analyse the gases released, providing information about the sample's composition and thermal stability. This led to a sample of 0.2 mg being pyrolysed at 600 degrees Celsius for qualitative analysis. Polymer calibration kits made of a series of 12 polymers dispersed in a powder diluent allowed for some polymers to be quantified by use of a calibration curve. The calibration curve for polystyrene showed a r-squared value of 0.99, demonstrating the robustness of the approach.

Results

Table 7 shows all products returned with a primary composition that was expected except for the bin-liner, the specific composition of which was unknown. Three products contained styrene-based polymers that could not be identified. Three products contained PLA as expected, with 1 product indicating the presence of polystyrene at levels greater than 10 mg/kg.

Table 7. Polymer identification of compostable products.

Item	Primary Composition	Potential Polymer Contaminant	Quantification (mg/kg)
Aqueous-coated Paper Cup	Cellulose	Poly(lactic) acid	N/A
PLA Cold Cup	Poly(lactic) acid	N/A	N/A
PLA-lined Paper Cup	Cellulose Poly(lactic) acid	Styrene-based polymer	N/A
Compostable Tea Bag	Cellulose	N/A	N/A
Bin Liner	Cellulose	Polybutylene terephthalate	N/A
Flat Brown Paper Bag	Cellulose	Styrene-based polymer	N/A
Newspaper	Cellulose	N/A	N/A
Cardboard Pizza Box	Cellulose	Polystyrene	10.02
Wooden Cutlery	Cellulose	N/A	N/A
Unlined Fibre Tray	Cellulose	Styrene-based polymer	N/A

Discussion

The polymer PLA is known to be only biodegradable under industrial composting conditions and anaerobic digestion (TÜV Austria et al., 2021). There is currently little evidence to show that PLA degrades in the natural environment, with studies showing negligible to low degradation rates in the aquatic environment (Ali et al., 2023) and in soil (Rudnik & Briassoulis, 2011). However, blending PLA with other polymers may change the degradation conditions and rate (Ali et al., 2023).

Since all three cups in this study contained PLA, there is the potential for the generation of microplastics/nanoplastics during the degradation of PLA products. If these cups were to be processed at a commercial composting facility, they would biodegrade/compost within a few months; in contrast, in the natural environment, the cellulose components may degrade but leave PLA plastic contamination.

The styrene-based polymers found in three of the products were unable to be identified due to the complexity of the sample matrix; however, it is conceivable that if a polymer is present in the sample, this may lead to plastic contamination. However, polystyrene contamination in the pizza box was unexpected because it had not been previously reported in the literature. This is of concern because polystyrene is well known for being very stable and difficult to degrade in the natural environment (Kim et al., 2021). The implications of polystyrene contamination in soil, in particular, include inhibition of crop growth, changes in enzyme activity and affecting pH and, thus, nutrient availability (Lian et al., 2024; Rassaei, 2024).

Regulations/Certifications/Standards

With the recent ban on single-use plastics in Aotearoa New Zealand, additional policies are being considered to phase out all PVC and polystyrene food and drink packaging (Ministry for the Environment, 2023). However, it is important to note that these guidelines target polymers as the primary composition and not as additives, such as those found in the pizza box studied in this report.

The definition of what constitutes plastic is a subject of ongoing debate among industry and scientists. This debate is significant as it has implications for regulations concerning plastic contamination. For instance, cellulose, though not typically perceived as a plastic, can be classified as such once processed and altered from its natural form. It is also worth noting the global effort to address plastic pollution through initiatives such as the Plastic Pollution Treaty, which aims to establish a global framework for addressing plastic pollution and its impacts on the environment and human health. The discussions around defining plastics and regulating their use will continue to evolve as we strive to mitigate the environmental impact of plastic waste.

Soil

Polymers breaking down into microplastics/nanoplastics have implications for changing the biophysical environment in soil. Water retention, texture and the relationships between microbial activity and soil aggregates are all affected by the addition of plastic contamination (De Souza Machado et al., 2018). Microplastics also have the ability to inhibit the degradation of other contaminants. For example, aged polystyrene has a particularly strong inhibitory effect on the biodegradation of the emerging pollutant tetrabromobisphenol A (TBBPA) (Chang et al., 2024). Polystyrene also has the ability to hinder the active sites of soil, causing the release of additives, as demonstrated for Cu (Peng et al., 2024).

3.4 Phthalates & Bisphenols

Introduction

Phthalates and bisphenols were identified in Part One of the project as additives that were well-studied in traditional plastics but insufficiently investigated in compostable products. Both phthalates and bisphenols refer to a group of chemicals commonly used as plasticisers to improve the flexibility and malleability of plastic products.

Methods

The following phthalates were analysed: DMP, DEP, DIP, DBP, DIBP, DNPP, DHXP, DHP, DNOP, DINP, DDP, DIDP, BBP, DEHA, DEHP and DINP + DIDP. For the bisphenol category, only BPA could be measured. To analyse these analytes in the compostable products, three grams of the sample were sonicated at room temperature in methanol to extract organic components of the sample into the solution (Zimmermann et al., 2019).

Results

Phthalate compounds (DEHP, DINP, and DBP) were only detected in the pizza box. In all other products, phthalate concentrations were below the LOR. The compound BPA was detected in three samples: the pizza box, the brown paper bag and the bin liner (Table 8).

Table 8. Results of Phthalates & BPA additives in compostable products.

Item	(mg/kg)			
	DBP	DEHP	DINP	BPA
Aqueous-coating Paper Cup	-	-	-	-
PLA Cold Cup	-	-	-	-
PLA-lined Paper Cup	-	-	-	-
Compostable Tea Bag	-	-	-	-
Bin Liner	-	-	-	0.04
Flat Brown Paper Bag	-	-	-	0.25
Newspaper	-	-	-	-
Cardboard Pizza Box	2.70	10.03	5.69	0.71
Wooden Cutlery	-	-	-	-
Unlined Fibre Tray (Sugarcane)	-	-	-	-

Discussion

DEHP values found in the pizza box are comparable to those found in literature, with packaging materials in one study showing 0.46–5.1 mg/kg DEHP (Fierens et al., 2012). Another study showed DEHP at concentrations of 2-39.8 mg/kg in recycled paper-paperboard intended as food contact materials(Suciu et al., 2013). Studies have also shown BPA present in paper board at 0.41-20.1 mg/kg and corrugated boxes at 2.31-10.8 mg/kg (Fierens et al., 2012; Yang et al., 2019). Overall, the DEHP values found in this study were comparable to those found in the literature. The typical range found in the literature for BPA in newspapers is 0.00568-5.28 mg/kg (Yang et al., 2019). In our study, no BPA was found in the newspaper tested.

Regulations/Certifications/Standards

Currently, there are no regulations in Aotearoa New Zealand, regarding the use of bisphenols and phthalates in soil or consumer products. The EU has regulations such as REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) and RoHS (Restriction of Hazardous Substances Directive) that restrict the use of certain hazardous chemicals, including bisphenols and phthalates, in consumer products. In the United States, the Consumer Product Safety Improvement Act (CPSIA) regulates the use of phthalates in children's products. The US Environmental Protection Agency (USEPA) also regulates bisphenols and phthalates under various programs. The Australian Government regulates bisphenols and phthalates under the Industrial Chemicals (Notification and Assessment) Act 1989 and the Australian Consumer Law.

Soil

If the pizza boxes are to be composted, it is highly likely that phthalates will migrate as a contaminant into the compost because phthalates are not bound to the product. After application of this compost to land, the phthalates will then enter the soil (Fasano et al., 2012). Cartwright et al. (2000) reported that the phthalate DEHP had no impact on bacteria numbers and functional diversity of the soil microbial community at a level of 100 mg/kg. The phthalate concentrations determined in this study (Table 9) were below the level that is potentially toxic to microorganisms. All phthalate concentrations were also below the guideline values for the beneficial use of organic materials on productive land in Aotearoa New Zealand (Fietje et al., 2017).

The bisphenol compound BPA has been shown to cause negative implications for plant growth at concentrations greater than 750 mg/kg dry soil and inhibition of root development at concentrations greater than 1000 mg/kg dry soil. Results determined in our study are well below the concentrations that cause an impact on plant growth and development (Cartwright et al., 2000). BPA is not detrimental to flora growth at the observed concentrations, but it can be taken up by crops like lettuce and collards (Dodgen et al. (2013), which may create human exposure pathways.

4 Ecotoxicity Testing

Introduction

Enzymatic assays were conducted to assess the impact of the series of compostable products and their additives on the enzyme activity in soil. The approach allows rapid screening for potential acute toxicity in microorganisms that perform essential soil functions. The nitrogen, phosphorus and carbon cycles were probed via the activity of the enzymes urease, phosphatase and invertase, respectively. Soil enzymatic activity was tested before and after dosing a soil sample with one of the five compostable products selected for this phase based on the results for additives (Table 9).

Table 9. Sample list for enzymatic activity testing.

Sample Number	Sample
1	Control (No compostable product)
2	Newspaper
3	Flat Brown Paper Bag
4	Pizza Box
5	Bin Liner
6	Unlined Fibre Tray
7	Trigene (Disinfectant)

Methods

The soil was collected from a nearby park (the University of Auckland, New Zealand, 36°50′58.669″S, 174°46′17.567″E) in April 2024. The top 10 cm below the grass cover was collected with a spade and sieved to 2 mm. The organic carbon content was approximately 22%. Sieved soil (40 g) with a moisture content of 40.47% was added to a glass beaker and preincubated for two weeks in the dark at 20°C to equilibrate the microbiome with the incubation conditions.

Each beaker received 1 gram of 1 mm x 1 mm cuttings of one compostable product. This mass was based on another study which used 1% and 2% weight compostable products in compost (Zhang et al., 2017); our study used 2.5% in soil as a realistic worst-case scenario. One beaker received trigene (2 mL), a solution of multiple quaternary ammonium compounds as active ingredients, which acted as a positive control with the idea that the addition of this hospital-grade disinfectant would stop all enzyme activity. Measurements were taken in triplicates at three-time points: just before the addition of compostable product (t=0), one day after (t=1), and again after seven days (t=7). Invertase and acid phosphatase were extracted and measured using commercial kits purchased from Sigma Aldrich, whilst the determination of urease followed a high throughput method previously published (Cordero et al., 2019).

The data was analysed using a 1-way ANOVA followed by Tukey's multiple comparisons test (comparisons of t=0 values across treatments) and with 2-way ANOVA with Dunnett's multiple comparisons test (to compare readings at t=1 and t=7 with that at t=0 for each treatment). Alpha was set to 0.05, and all the analyses and graphs were produced using GraphPad Prism 6.0.

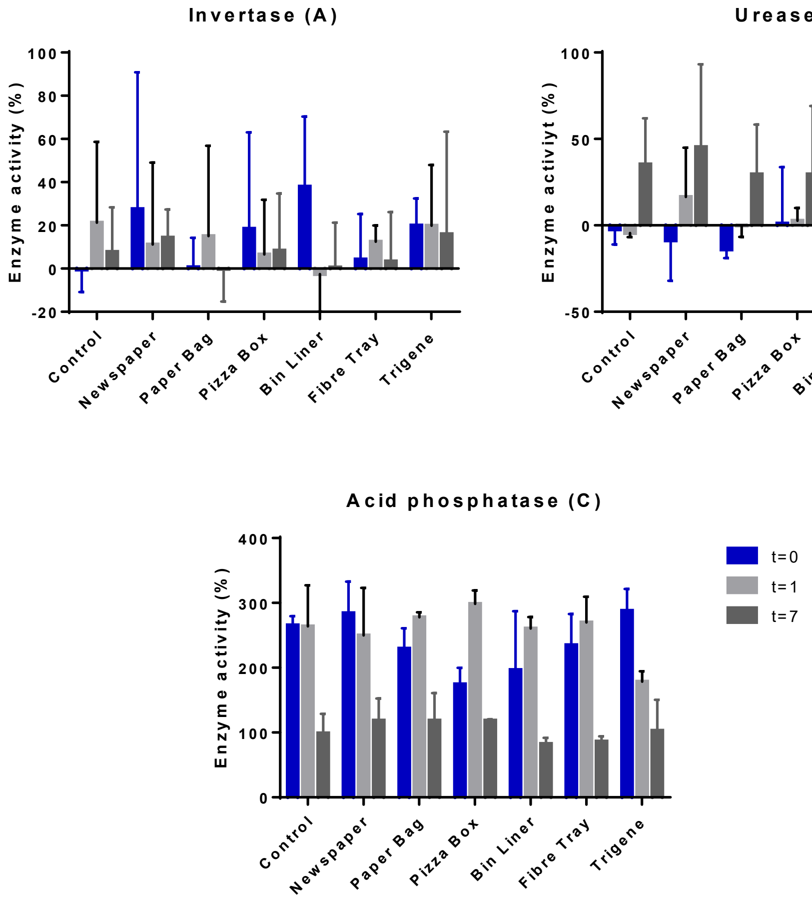

Figure 1. Soil enzyme activity before (t=0) and after (t=1 and 7 days) the addition of compostable products for (A) Invertase, (B) Urease, and (C) Acid phosphatase. Enzyme activity was measured by UV/Vis absorbance relative to blanks (no enzyme activity). Error bars represent the standard deviation between triplicates.

Results

The acute toxicity of a compostable product would lead to a significant decrease in enzymatic activity at t=1. At t=0, before any compostable products were added, the levels of invertase activity were statistically similar across all treatments ($p>0.05$, Figure 1A), indicating that urease activity was similar for all soils at the start. The invertase activity did not change significantly over time for both the control (no compostable product added) and the treatments that received compostable products. This result shows the absence of acute effects of compostable products on invertase activity after 1 and 7 days of exposure. Similar results were observed for urease and acid phosphatase, with no significant differences in the readings at t=1 and t=7 with that at t=0 (Figures 1B and 1C). Note that the decrease in acid phosphatase measured at t=7 is not indicative of acute impacts, as it was observed in both the control and treatments. This result is likely due to an issue with the experiment, as samples exhibited a yellow colouration that interfered with the measurement.

Also, the positive control, trigene, showed minimal changes over time, suggesting that the concentration of trigene was insufficient to provoke inhibition of the soil enzyme activity or that the active ingredients in trigene are not effective against the enzymes measured.

Discussion

The three enzymes tested are related to different nutrient cycling processes taking place in soil. Invertase catalyses sucrose to glucose and fructose, which helps provide an energy source for biota. It also plays a major role in the transformation and cycling of organic carbon and thus serves as an indicator of soil general bioactivity (Wu et al., 2023). Urease hydrolyses urea into ammonia and carbon dioxide, which is a key step in the nitrogen cycle (Antonious et al., 2020). Phosphatase breaks down organic compounds into phosphate, contributing to the recycling of soil phosphorous (Sun et al., 2020).

Overall, our results show that compostable products had a limited impact on the three enzyme activities, but it is essential to recognise a few limitations of the experiments conducted in the context of a short project time frame.

(1) The short-term experiments do not account for the transformations that would occur during the composting process, where compostable products can be decomposed and release additives that may be toxic to soil health. Due to the short project timeline, our work only considered the direct application of compostable products to soil, which is not the most realistic scenario.

(2) The tests only consider acute effects, whereas chronic (longer-term) effects are more likely to be observed, especially after the repetitive application of compost that may be contaminated.

(3) Soil hosts an incredible biodiversity, and the bacterial activities probed here represent only a small fraction of this complex ecosystem (Anthony et al., 2023). 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.

(4) Interpreting soil enzyme activity testing is challenging due to the inherent complexity of soil, which hosts numerous ecological and biogeochemical processes within the microbial community. These complexities can obscure the effects one seeks to measure.

We thus recommend that further research is conducted on the long-term impact of "composted" compostable products, with a more comprehensive assessment of the organisms representing different soil trophic levels and potential chronic effects of mixtures.

5 Key Take-home Messages

This study analysed ten compostable products for a variety of additives and their potential negative impact on soil health. The results were discussed with stakeholders from the central government agencies, composting facilities, manufacturers, users, and scientists. While we acknowledge the limitations of our study (e.g., analysing only ten products), we identified compounds of concern (Table 10) and key take-home messages as follows:

Table 10. Summary of compostable products analysed. (Green representing no concern to red, which is of concern)

Item No.	Item	TF (PFAS)	Heavy Metals	Microplastic	Phthalates	Bisphenol
1	Aqueous-coating Paper Cup			Poly(lactic) acid		
2	PLA Cold Cup			Poly(lactic) acid		
3	PLA-lined Paper Cup			Styrene-based polymer		
4	Tea Bag					
5	Bin Liner			Polybutylene terephthalate		BPA
6	Flat Brown Paper Bags			Styrene-based polymer		BPA
7	Newspaper		Cu			
8	Cardboard Pizza Box		Cu	Polystyrene	DBP, DEHP, DINP	BPA
9	Wooden Cutlery					
10	Unlined Fibre Tray					

Additives Analysis: The analysis costs for additives are high, and there are discrepancies between methodologies. Using TF as a screening tool for PFAS is recommended by European or Australian standards, but our results show that TF values can be misinterpreted. Establishing baseline levels for additives in Aotearoa New Zealand for food, soil, and compost is crucial for setting meaningful and specific acceptable levels. These levels may be lower than those overseas not only to improve alignment with Te Ao Māori values but also because a lower threshold (e.g. from 100 down to 25 mg/kg TF) would direct products (e.g. cardboards) to better-suited recycling facilities instead of composting, where they may be the source of undesirable contaminants.

Further studies are needed to assess the long-term toxicity of additives, especially when they degrade and interact with the soil over time. The interaction between additives and organic matter in composting processes requires more investigation to determine their influence on compost quality and soil health. Also, there is a need to identify and study the degradation products of additives, as they may have different environmental impacts compared to the original compounds.

Regulatory Tools: The regulatory space in Aotearoa New Zealand lacks clarity, particularly regarding oversight of chemicals like PFAS in manufactured products in compostable packaging. Products are unlikely to be tested unless there is a complaint. Ensuring enforcement and compliance is challenging due to resource constraints, impacting the establishment of standards and certification schemes.

Composting Facilities: Compostable products face low acceptance at end-of-life facilities due to technical barriers, lack of transparency about the composition of products to be composted, and limited access to suitable facilities. The perception of 'unknown content' contributes to this issue, along with the unknown fate of contaminants going through different composting processes (i.e., home/industrial composting, vermicomposting, or anaerobic digestion).

Compost Quality: The lack of standardised testing for additives in compost raises concerns about potential contamination and reluctance to use it as fertiliser.

Communication and Certification: Mandating certification and labelling following Australian or European standards could address the lack of knowledge and clarity. There is an urgent need to improve consumer education, reduce greenwashing, and create incentives that will support consumers' behavioural changes.

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