Integration of Agricultural Systems for Environmental Sustainability:

Vermicomposting Organic Resources for Waste Management and Food Production in a Circular Economy

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Abstract

Food production creates organic waste. Dissolved air flotation (DAF) sludges from meat processing are problematic to dispose of; they are odorous, have high moisture contents and are rich in nutrients. Direct land application without stabilisation of nutrients is common. Paper wastes can often be recycled, but food-contaminated paper wastes are usually landfilled. Nutrients in these two organic resources are therefore usually wasted. This research demonstrated that the compost worm (*Eisenia fetida* Savigny) could produce vermicompost from novel mixtures of chicken DAF sludge and cardboard, meeting the New Zealand Standards for vermicasts and provided a beneficial effect on plant growth.

This research investigated whether commercially produced vermicast applied to onions, potatoes and maize affected yield and/or quality over three consecutive years, with crop rotation on a market garden farm. While international field trials have shown vermicast to improve crop yields, this has not been investigated in rotational crop farming for maize, potatoes and onions. It also has not been conducted in New Zealand at the scale in this thesis. The treatments applied were annual applications of either chicken litter applied at 3 t fresh matter (FM)/ha, vermicast applied at 12.5 t FM/ha or 25 t FM/ha. The treatments were compared to a Control (normal farm management). All treatments, including the Control, received normal fertiliser rates. The trials showed that vermicast applied at 25 t fresh matter (FM)/ha increased onion density and yield (with estimated farmgate profit of >$800/ha), as well as maize grain kernel mass compared to the Control in the third season. This season was the driest, indicating the vermicast provided benefits to crops under abiotic stress. The chicken litter treatment reduced onion density in the second and third seasons. In the third season, this led to an increase in average onion bulb mass, but did not translate to an increase in yield above that of the Control.

Additional glasshouse studies were conducted on the application of commercially produced vermicast to determine whether the method or timing of application impacted onion bulbs under glasshouse conditions. Another study investigated the potential for vermicast to supplement diammonium phosphate (DAP) fertiliser in a phosphorus (P) -sparing trial in onions on a low Olsen P soil. Final soil Olsen P contents from treatments with 12.5 t FM/ha vermicast and 100% and 75% of recommended P were not significantly different to the Control (100% P and no vermicast). No effect of timing or supplementation of DAP was found on onion size or mass, though these trials were found to be underpowered. The effect of vermicast application timing in relation to crop

production has not previously been investigated. Neither has the potential for vermicast to supplement imported phosphate fertiliser on low Olsen P soils.

The outcome of this thesis is that beneficial vermicast can be produced from organic wastes and has potential to improve food production in New Zealand. It may also be possible to use vermicast to reduce reliance on conventional fertilisers such as DAP.

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Key definitions and abbreviations

Only key terms are defined here. Other definitions can be found within the relevant text.

Term	Definition
Chicken litter	A by-product of broiler (meat) chicken farming consisting of bedding material e.g. sawdust and manure.
Compost worms	Epigeic earthworms that live in rich organic matter above the soil and can be used in vermicomposting to convert organic wastes into vermicast. *Eisenia fetida* is a common species used and is the species researched and trialled in this thesis.
DAF sludge	A sludge produced through the process of Dissolved Air Flotation during wastewater treatment. Suspended solids in effluent are flocculated and floated to the surface where they are scraped off as a nutrient rich sludge, leaving an effluent with higher clarity behind.
Vermicomposting	(Earthworm farming) the process of earthworms decomposing organic matter through ingestion and excretion, forming vermicompost/vermicast.
Vermicast	(Earthworm casts/poo) where ≥90% of the original material has been ingested and excreted as casts <1.18 mm diameter (Standards New Zealand, 2005).
Vermicompost	Partially vermicomposted material where vermicast is present at <90% of the final product. Some of the feedstock/compost material remains uneaten by compost worms.
Vermiculture	Breeding and cultivation of earthworms. Unlike vermicomposting where the focus is on converting feedstock into vermicast, the focus of vermiculture is earthworm biomass production.

Chapter 1
Introduction

1.1 Background

New Zealand is widely recognised as an agricultural nation, particularly for dairy production. While only a small portion (1.1%) of agricultural land is used for horticultural production, the industry contributes significantly to the New Zealand economy. In 2025, fresh and processed fruit and vegetable exports had a total export value of $6.85 billion (Ministry for Primary Industries, 2025; United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025). Conventional cropping methods such as cultivation and frequent herbicide/pesticide use have direct impacts on soil health and substantial fertiliser use such as superphosphate and urea leads to loss of excess nutrients to the environment (Edmeades, 2003; Sparling & Schipper, 2004; Turmel *et al.*, 2015; Gallardo, 2024).

Phosphorus (P) is essential for food production. New Zealand is reliant on imports of rock phosphate to produce derivative fertilisers such as superphosphate to support food production. Alternative sources of P fertilisers such as chicken litter are available, however its characteristic pungent odour, potential for pathogen transmission and lack of nutrient stabilisation can have negative impacts on production. New Zealand's poultry meat industry produces about 120 million broiler chickens/year. Hatched chicks are grown until about six weeks of age before processing for human consumption. Broiler facilities use a wood-based bedding material (litter) that accumulates manure and occasional mortalities over the six-week period. Large quantities of litter are produced by the industry (an estimated 225,657 t fresh litter from 120 million broilers in 2022). After broilers are sent for processing, the litter is replaced (PIANZ & EPFNZ, 2012; PIANZ, 2022). Chicken litter is a popular soil conditioner/nitrogen (N) fertiliser, however its management and application are poorly regulated, globally and in New Zealand (Kyakuwaire et al., 2019). In New Zealand, there are no regulations or industry standards other than a recommendation that stock do not graze pasture that has received chicken litter within 21 days (PIANZ & EPFNZ, 2012). There are also guidelines that require chicken litter not to be applied to crops within a specified period of harvesting (Fresh Produce Safety Centre Australia & New Zealand, 2019). These recommendations address potential pathogen risk, but neither addresses management of the litter to ensure nutrient

stabilisation. While chicken litter offers benefits to soils and crops, it also carries environmental risks such as phosphorus (P) accumulation in soils, nutrient leaching and runoff, introduction of pathogens, and odour and greenhouse gas emissions. Currently, guidelines and regulations exist for other soil conditioners, composts and mulches (Standards New Zealand, 2005) and biosolids (New Zealand Water and Wastes Association, 2003), but not for chicken litter. Instead, ensuring safe management tends to fall to end-users in the horticulture and pastoral farming industries.

Another source of P is from earthworm castings (vermicast) which are known for their value as a soil conditioner and plant growth stimulant (Blouin *et al.*, 2019). Large scale vermicomposting facilities can process organic wastes in outdoor windrows using earthworms to produce vermicast. These have only recently started to see large scale applications in agriculture in New Zealand (Quintern, 2014). Vermicomposting is useful for processing organic wastes such as biosolids from municipal and food processing wastewater treatment plants (Eastman *et al.*, 2001; Ali *et al.*, 2015). Dissolved air flotation (DAF) sludge from chicken processing plants and non-recyclable paper waste have limited management/disposal options.

Meat processing of broilers produces a variety of organic wastes. Some of these are managed through existing markets e.g. heads and viscera can be sold for petfood, while feet can be sold for human consumption. Other organic wastes such as solids from washdown water are processed in a wastewater treatment plant. Depending on the plant, wastewater will undergo processing to manage nutrient loads (especially N), solids content and pathogens. Nitrogen loads of effluent can be predominantly managed through controlling the processes of nitrification (ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-)), then anaerobic denitrification (nitrate (NO_3^-) to nitrogen gas (N_2)). Solids content can be managed through dewatering technology such as DAF, producing a nutrient-rich, high moisture sludge (Artika Devi, personal communication, July 15, 2025).

The high moisture content makes DAF sludge expensive to landfill. Disposal to land is regulated through Resource Consents. Direct application of organic waste products (such as DAF sludge and chicken litter) to pasture or crops allows for recovery of nutrients and can be used to increase yield. However, these wastes are not fully stabilised so organic N mineralised to ammonia (NH_3) produces offensive odours. Ammonia is eventually converted nitrate (NO_3^-) which is highly mobile in soil and contributes significantly to water pollution. Dissolved air flotation and other sludges require the addition of a high-carbon bedding material, such as paper, for vermicomposting. While about half of the paper collected in New Zealand is destined for recycling either locally

or internationally, significant volumes of paper waste that do not enter the recycling system are sent to New Zealand's landfills. In 2020, it was estimated that 218,211 t paper was sent to landfill in New Zealand (Ministry for the Environment, September 9, 2021).

Food-contaminated paper waste unsuitable for conventional recycling may be a suitable carbon input for a vermicomposting feedstock with DAF sludge from poultry processing. As well as the vermicomposting process providing an alternative management method for problematic organic wastes, it also produces vermicast as a by-product. Vermicast provides benefits to soils and plants, for example through increasing soil water holding capacity and providing a source of mineralised nutrients available to plants for uptake. While these are only two of many benefits, both characteristics are valuable to crop production and vermicast has been widely recognised to improve crop yields in a variety of species (Blouin *et al.*, 2019).

1.2 Problem statement and research objectives

Dissolved air flotation (DAF) sludges from meat processing are problematic to dispose of. They are odorous and have high moisture and organic nitrogen contents, resulting in high ammonia concentrations through nitrogen mineralisation. The overarching goal was to determine whether vermicomposting using *Eisenia fetida* compost worms could be a suitable method to stabilise poultry plant Dissolved Air Flotation (DAF) sludge and improve crop production.

While vermicast application has been shown to improve soil quality and crop health and yield, this has not been investigated in rotational crop farming for crops such as maize, potatoes and onions. Furthermore, neither the effect of vermicast application timing in relation to crop production has been investigated nor whether vermicast is suitable for supplementing imported phosphate fertiliser on soils, including those with low Olsen P.

The hypotheses explored in this research include:

i. Vermicast can be successfully produced from chicken poultry DAF blended with cardboard.
ii. Vermicast application timing impacts crop yield.
iii. Vermicast application is beneficial for crop yield on soils with low Olsen P.
iv. Vermicast application to soils improves crop yield and quality (more so than chicken litter) on a commercial market garden.

1.3 Thesis structure

The thesis is structured as follows:

Chapter 2 starts with a broad overview of food production and leads into production issues, especially nutrient availability and pollution. Alternative nutrient sources to conventional fertilisers are discussed and vermicomposting of organic wastes is proposed. The benefits of vermicast and potential for its use in New Zealand agriculture are addressed. The novelty of the research in this thesis is outlined, and the review wraps up with the application of a circular economy principles and how the proposed system could work. The three following chapters report on the trials completed to address the research gaps.

Chapter 3 describes pilot and lab scale vermicomposting trials where DAF sludge from chicken processing was vermicomposted with cardboard. The pilot trial was designed to prove this DAF could be vermicomposted and find the optimal ratios of DAF and cardboard as a feedstock for *Eisenia fetida*. The lab scale trial aim was to produce vermicast that met the NZS 4454:2005 New Zealand Standard for composts, soil conditioners and mulches (Standards New Zealand, 2005).

Chapter 4 describes the glasshouse trials conducted to examine the timing of the application of industrial vermicast to onions to two different soils and as a supplemental source of P fertiliser on onions grown on a low Olsen P soil.

Chapter 5 describes the three-year trials comparing the effect of vermicast application on commercial crops of maize, potatoes and onions to crops with chicken litter and crops with no treatment.

Chapter 6 contains the overall conclusions of the thesis and recommendations for future work.

Chapter 2
Literature review

2.1 Introduction

This chapter reviews published literature available on vermicomposting organic wastes and the use of vermicast at scale for food production. The review begins with a broad overview of food production highlighting issues with nutrient availability and pollution. Alternatives to conventional fertilisers including the commercial scale production of vermicast from organic wastes in agriculture are discussed. The review concludes with a discussion of circular economy and agroecological principles as the basis for integrating agricultural systems. The chapter ends with an overview of how a proposed system could work to enable environmental sustainability in food production.

2.2 Food production

2.2.1 Global food production

Global food production has been increasing over time with a 28% increase in yield over the 20 years between 1985 and 2005 (Foley *et al.*, 2011) and a further 28% increase reported over the 13-year period between 2010 and 2023 (FAO, 2024). The majority of global food crops (62%) are produced for direct human consumption, while 35% are utilised as animal feed (for meat and dairy production), and the remaining 3% are used for other purposes such as bioenergy and seed production (Foley *et al.*, 2011). Cereal crops such as maize, rice, wheat, barley and sorghum are the dominant food crops grown worldwide. In 2023, over 3 billion tonnes of cereal crops were produced, followed by nearly 2.5 billion tonnes of sugar crops (predominantly sugar cane and sugar beet), 1 billion tonnes of vegetables (dominated by tomatoes and onions) and 1 billion tonnes of oilcrops (dominated by oil palm fruit and soya beans). The remainder of production was made up of just under 1 billion tonnes of root crops, the same amount of tuber crops (predominantly potatoes), and 0.25 billion tonnes of other crops (FAO, 2024).

2.2.2 New Zealand food production

According to United Fresh New Zealand Incorporated and Bioeconomy Science Institute (2025), New Zealand has >4,200 growers producing fruit and vegetables. Fresh fruit and vegetables are supplied directly to grocery retailers, greengrocers, markets,

community groups, food services, delivery services, wholesalers and ripeners, packhouses and post-harvest processers.

Half of New Zealand's land is used for agriculture (including horticulture) and forestry, with the majority of products being exported (Rush & Obolonkin, 2020; Ministry for the Environment & Stats NZ, 2021). Agricultural and horticultural land in New Zealand is divided into the following uses: sheep (35.3%), beef (23.4%), dairy (19.1%), forestry (13.8%), grain (4.2%) and horticulture (1.1%) (Ministry for the Environment, 2021a). Although dairy does not dominate agricultural land use, New Zealand is known for its dairy exports, and the industry appears to continue growing, with dairy production increasing in 2024. While New Zealand does not produce as much milk volume as larger countries (only 2% of global milk production), amongst the European Union and the United States, it is known as one of the three major dairy exporters. Combined exports between these three major producers is anticipated to account for 70% of global milk exports (FAO/OECD, 2025).

In 2019, cropping and horticulture made up 2% of New Zealand's total land area (Ministry for the Environment, 2021a). In 2025, it was reported that 74,286 ha of land was under horticultural fruit and vegetable production (about 0.3% of New Zealand's total land area) (Ministry for Primary Industries, 2025; United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025). In 2021, the dairy, meat, wool, forestry, horticulture, and arable agriculture sectors contributed over $62.0 billion to the New Zealand economy (Ministry for Primary Industries, 2025). In 2025, fresh and processed fruit and vegetable exports had a total export value of $6.85 billion, accounting for approximately 1.6% of nominal GDP. Kiwifruit is the main fresh fruit/vegetable export in New Zealand (60.1%), followed by apples (18.0%) and onions (2.1%). Asia is the largest importer of New Zealand fresh fruit and vegetable exports, with kiwifruit being their main import.

In 2020, the COVID-19 pandemic disrupted the horticultural sector, particularly in resources for harvests and general management, triggering a response. An action plan (the Aotearoa Horticulture Action Plan; AHAP) was developed between 2020-2023 collaboratively by industry, government, Māori and research providers. In 2023, it was launched. Consequently the horticultural industry has a target of doubling the farmgate value of New Zealand horticultural exports by 2035 (Horticulture New Zealand, 2025).

The roadmap is compiled of five pillars: sustainable growth of the horticulture sector under a changing climate, optimising the value chain of domestic and exported goods, tripling Māori participation in high value horticulture, a strong research and

development programme that incorporates Mātauranga Māori (Māori knowledge), and attracting and retaining skilled workers in the sector.

2.2.3 Important food crops in New Zealand

The following New Zealand regional statistics for land under fruit and vegetable cropping are based on a minimum of 100 ha sown in a particular crop of a region. The data are from 2022 Census statistics, reported in the Fresh facts 2025: New Zealand's fresh fruit & vegetable industry report. The authors of these data acknowledged that not all participants completed their Census documents, resulting in error in the actual land area estimates, and that planting area fluctuates. According to the report, horticulture in Northland and the Bay of Plenty regions are dominated by the orchard crops avocado and kiwifruit. Gisborne is dominated by squash, Hawke's Bay by apples, Manawatu and Waikato by potatoes, and Auckland by onions. In the South Island, Marlborough and Westland are dominated by sweetcorn, Canterbury by potatoes, Otago by cherries, Southland by carrots and Tasman by apples. No fruit and vegetable crops were listed in Taranaki or Wellington regions (United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025). Onions and potatoes are dominant fruit and vegetable crops in the Auckland, Waikato, Manawatu and Canterbury regions. Maize is a grain crop and was not included in the above statistics, however, it is a popular grain (Booker, 2009). The following sections discuss the three crops researched in this thesis: onions, potatoes and maize.

2.2.3.1 Onions

Onions (*Allium cepa* L.) are a popular culinary vegetable with a pungent flavour that belong to the *Alliaceae* family. They are monocotyledonous biennial plants, usually cropped as annuals (Currah *et al.*, 2012). They are the most common fresh fruit/vegetable grown crop in Auckland, and Canterbury regions in New Zealand. They are predominantly an export crop, with approximately 85% of production being exported. In 2025, the value of NZ onion exports to other countries was $69m to Asia, $46m to Continental Europe, $18m to the Pacific Islands and $8m to UK and Ireland. Given the size of the New Zealand onion industry (85 growers and 18 export members), there is a dedicated industry group for production called "Onions NZ" (United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025; Onions New Zealand Inc., n.d.-a).

2.2.3.1.1 Onion production

Onions are sown in New Zealand winter, between May and September and harvested between November and May, depending on the variety and planting region. This allows complimentary supply of fresh onions to customers in northern hemisphere countries who are in their off-season when New Zealand onions are ready for export (Onions New Zealand Inc., n.d.-b).

Onions are harvested ideally at the end of their growth period, after a large proportion of the crop undergoes top fall (the upright leaves fold over at the neck). At this stage the bulbs will generally have reached their full size (Eamon Balle, personal communication, March 10, 2026). Harvesting requires a few stages. First, onions are lifted i.e. the roots are cut. This can be done mechanically by pulling the onions out of the ground, tearing the roots near the bulb. They are then left on top of the soil to cure. Dry skins form and the neck of the bulbs dry up and close tightly. This slows gas exchange and water losses, as well as providing protection from pathogens. This is desirable as the skin is what protects the bulb during processing. After this initial curing stage, the onions are harvested and stored in a packhouse in wooden crates for a minimum of 10 days before being graded for size and quality (Currah *et al.*, 2012; Onions New Zealand Inc., n.d.-b).

2.2.3.1.2 Onion growth

The bulbs are the desirable part of the onion in common brown and red varieties. A single seed yields one bulb in brown and in red onions, while for shallots, a morphologically distinct subgroup/aggregatum variety, one bulb yields multiple bulblets attached at the base when mature.

The common onion bulb is a storage organ for water, energy and nutrients. It is formed from two types of leaves. The outermost leaves produce a lamina, a hollow, green blade forming the foliage. The leaf bases are cylindrical and swell to enclose the fleshy scales during bulbing. The scales are non-green and bladeless i.e. they lack a lamina (hollow leaf blade) and are not for photosynthesis, so lack chlorophyll. They form further storage capacity at the heart of the bulb. All growth (leaf and root) originates from the apical meristem at the centre of the base plate. This is a flattened, disc-like stem also found in other monocots such as grasses. New leaves grow from the apical meristem and through a hole in the previous leaf at the top of the sheath (the cylindrical part of the leaf that swells during bulbing). This makes the outermost leaves the oldest (Bertaud, 1986; Currah *et al.*, 2012).

Optimal temperature and photoperiod (relative length of day and night in a 24-hour period) are essential for producing a high yielding onion crop (Khokhar, 2017). Photoperiod is the primary driver of bulb development (Bertaud, 1986; Currah *et al.*, 2012; Khokhar, 2017). Onions are classified as long or short day varieties and a wide variety of cultivars has been developed for production at specific latitudes (Currah *et al.*, 2012). While photoperiod is the primary driver of bulbing, temperature also has a significant effect, as do other abiotic factors such as light intensity and quality, plant density (competition), nitrogen supply and water availability (Khokhar, 2017).

According to Brewster (1977), the optimal temperature for onion growth is 25 °C during the period of maximum growth. They also report that all tested varieties onions have a low maximum growth rate compared to other vegetable species such as Brussels sprouts (*Brassica oleracea* L. var *gemmifera*). Despite slower growth rates than other vegetable crops, onions tend to require more N, P and K fertilisers (Brewster, 1977; Ghaffoor *et al.*, 2003).

Onions grown in soil do not have root hairs. Compared to other shallow-rooting species, onions have comparatively thick roots, giving them a low surface to volume ratio (Brewster *et al.*, 1975; Brewster, 1977). This along with relatively short root systems (up to 60 cm) make it more difficult for onions to extract nutrients such as P from soils. However, if onion roots are infected with vesicular-arbuscular mycorrhizal fungi (*Endogone* species), nutritional supply to the onion is increased as the mycorrhizal fungi access and exchange soil nutrients such as P with the onion plant for carbohydrates. This desirable, symbiotic relationship essentially increases the onion root surface area, promoting nutrient uptake and plant growth. It appears to be most beneficial when P supply is low, though the amount of P in the soil in an experiment by Hayman and Mosse (1971) did not appear to affect mycorrhizal infection of onion roots.

2.2.3.1.3 Onion pests and diseases

Onions are susceptible to a variety of pests and diseases both during growth and in storage and a variety of factors can affect their incidence. For example, onions require adequate N in early growth stages, but too much in later growth or maturity can result in rapid leaf growth and increased susceptibility to disease such as bacterial soft rot (*Pectobacterium carotovorum*), and therefore poor storage (Fullerton *et al.*, 1986; Currah *et al.*, 2012). Other diseases such as white rot pink root, downy mildew, botrytis can have economic impacts on onion crops and infect onions via different routes e.g. through infected soil, contaminated machinery, diseased seed or airborne spores. Weather

conditions affect bacterial and fungal diseases as well as creating conditions conducive to growth of pest populations such as thrips, aphids and cutworm. Growing commercial onion crops requires vigilant monitoring and careful management to minimise losses (Wright *et al.*, 2015) as well as a need for good nutrient management .

2.2.3.2 Potatoes

Potatoes (*Solanum tuberosum* L.) are a starchy staple crop from the *Solanaceae* family. The potato plant is a dicotyledonous perennial that produces underground storage tubers – the edible potato. Potato tubers are carbohydrate storage organs, however they are also valued for their nutritive value. They contain approximately 10% protein on a dry mass basis as well as containing complex carbohydrates, minerals, vitamins e.g. C, micronutrients, phytonutrients/antioxidants and dietary fibre (Raigond *et al.*, 2020).

2.2.3.2.1 Potato production

As well as being considered a staple crop globally, potatoes are the most common fresh fruit/vegetable grown crop in Waikato, Manawatu and Canterbury regions (FAO, 2024; United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025). There is a dedicated industry group for potato production in New Zealand (Potatoes New Zealand).

Since the 2021-2022 financial year, the number of New Zealand potato growers has decreased from 172 to 151 in the 2024-2025 season, yet the total area of land under potato production increased 15.7% from 8,951 to 10,358 ha over the same period.

Thirteen percent of the total value of New Zealand potatoes and products are from exports. In 2025, the value of New Zealand potato exports to the Pacific Islands was $38m, with $24m for table (unprocessed) and $14m for preparations (United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025). Production of fresh potatoes in New Zealand is sufficient to cover domestic demand (Eamon Balle, personal communication, March 10, 2026). In 2024, potato imports to New Zealand made up 0.007% of all imported fresh fruit and vegetables. This dropped to 0.001% in 2025 (United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025)[1].

Fresh potatoes tend not to be imported or exported globally as the risk of pest and disease transmission is high (Dehnen-Schmutz *et al.*, 2010). A webpage on the Potatoes New Zealand website lists 25 sector risk organisms, that if introduced to New Zealand

[1] 1.52 t potatoes ÷ 149,412.81 t = 0.007% total imported fresh fruit and vegetables 9.76 t potatoes ÷ 141,009.76 t = 0.001% total imported fresh fruit and vegetables (United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025).

could have widespread negative impacts on the potato industry (Potatoes New Zealand, n.d.).

Concern from the potato industry over increasing costs of potato production has been recorded over recent decades. Yields have not been increasing – they have remained static at 50-60 t FM/ha despite advances in management technologies such as irrigation, fertilisation, and pest and disease control (Sinton *et al.*, 2013). In 2012, Reid *et al.* (2016) investigated whether improper fertilisation was the reason that growers were unable to increase potato yields to the modelled potential of 90 t FM/ha. In their industry and Crown Research Institute-funded study, the target paid yield (excluding undersized tubers) was 65 t/ha (13.3 t/ha dry) for Russett Burbank and Innovator processing varieties for four farms in Canterbury. Despite a yield gap, all sites achieved >65 t FM/ha yields. Their study showed that only one site, which was under fertilised, showed a significant yield response to increased fertiliser (N, P K and Ca doubled in different combinations with 12 treatments in total). The other three sites did not respond to higher fertiliser applications, though the yield gap (at all four sites) between potential and actual yield was >1, indicating that despite achieving the target 65 t FM/ha, management practices were limiting yield. Potential yield was defined as a variety's best performance given the cultivar and seasonal weather restrictions.

Sinton *et al.* (2013) studied the effects of soil health (compaction, aggregate size and disease inoculum) on Russett Burbank and Innovator yields in Canterbury. They found that root vigour was essential for producing higher yields. Notably, poor root vigour and lower yields were recorded in plants grown on sites with a compaction layer and/or where the plants were affected by disease. However, despite evidence that long-term potato cropping impacts soil health, there was no effect of cropping history apparent in their data. They rated the following factors as the most important contributors to their observed yield gaps of 20-42 t FM/ha: root diseases, soil compaction, foliar disease, uneven plant emergence, mismatched irrigation, weed competition, herbicide damage, planting issues and machinery damage. A later study by Sinton *et al.* (2020) (studying the same processing varieties: Russett Burbank and Innovator) reported that average yields in Canterbury were 55 t FM/ha, almost half the measured potential of 90 t FM/ha. They investigated the effect of enhanced soil structure – a measure of soil health via aggregate size distribution on the yield gap in Russett Burbank and Innovator potato varieties. Soils with pasture-dominant rather than cropping-dominant histories had higher disease incidence, however they also had better soil quality which resulted in higher yields of +10 t FM/ha on average. Reportedly, the results of the large research projects (including

Sinton *et al.* (2013)) undertaken in the Canterbury region have provided useful information to local growers who place greater weight on the history of their land when considering where to grow potato crops (Sinton *et al.*, 2022).

2.2.3.2.2 Potato growth

Potatoes are grown commercially from 'seed' tubers, (not seed). Potato seeds can be used by breeders to develop new varieties, but are not used for tuber production as each seed within a fruit is genetically different. When dormancy is broken (by environmental factors such as temperature), seed tubers grow sprouts from nodes on the tuber. The sprout becomes the stem of a new plant. In commercial settings, seed tubers are sown in moulds before sprouts form to avoid damage. When the sprouts encounter light after growing upwards through the soil, they form compound leaves from aboveground nodes on the stem. Leaves develop in a spiral pattern along the elongating stem as the shoot grows (apical growth).

Soon after sprouts form, roots develop from nodes located up the length of the new stem. Later, stolons form from the underground nodes along the stem. These are modified stems that grow horizontally through the soil and form underground tubers (carbohydrate storage organs, also modified stems) under the right conditions. Flowering also occurs.

The ratio of the plant growth hormones gibberellic acid and abscisic acid, divert plant reserves to shoot or tuber production. Gibberellic acid is a growth promoter. At high levels it directs plant reserves to shoot production. Abscisic acid is a growth inhibitor. At high levels it slows shoot production and promotes tuber growth. Other factors also influence tuber formation such as high nighttime soil temperatures and excessive N availability, both of which limit tuber production (Thornton, 2020).

The chemical composition and therefore the quality of potato tubers is affected by environmental conditions both in production and storage. As potato plants mature, the shoots (the haulm/foliage above ground) naturally senesce (die off). At this stage, the skins of the tubers thicken and attach more firmly to the tuber. Dry matter, measured as specific gravity in the potato industry, increases. Sugars (the product of photosynthesis during the growing period) stored in the tubers are converted to starch. This is desirable for the crisping and frying potatoes as the presence of reducing sugars results in darker chips upon frying – an undesirable characteristic in these industries (Bindi *et al.*, 2006; Thornton, 2020). Allowing potato plants time to mature is also important for storage as

tubers remain dormant longer, have lower respiration rates and are less susceptible to storage diseases (Thornton, 2020).

2.2.3.2.3 Potato pests and diseases

Potatoes are susceptible to a number of pests and diseases whose presence is often region dependent. Disease examples include common scab (*Streptomyces scabies*), powdery scab (*Spongospora subterranean*), stem canker (*Rhizoctonia solani*) (Reid *et al.*, 2016), early blight, (*Alternaria solani)*, and late blight (*Phytophthora infestans*) (Sinton *et al.*, 2022). Examples of pests causing economic damage to potato crops in New Zealand are: root-knot nematode (*Meloidogyne fallax* and *M. hapla*), potato tuber moth (*Phthorimaea operculella* Zeller) whose larvae mine potato foliage and stems and burrow into tubers (Kroschel & Lacey, 2008), green peach aphid (*Myzus persicae* Sulzer), which is one of the main vectors for potato leaf roll virus (Stufkens & Teulon, 2001) and tomato potato psyllid (*Bactericera cockerelli*) which transmits a bacterium (*Candidatus Liberibacter solanacearum*) causing significant economic losses through damage to plants and 'zebra chip' in tubers, which can result in rejection of large quantities of processing potatoes (Munyaneza, 2012; Anderson *et al.*, 2013). As well as chemical management methods, crop rotation (Wright *et al.*, 2015) and cultivar selection (Anderson *et al.*, 2013) can be used to reduce disease pressures. Improvements in soil health such as soil structure can also alleviate effects on yield (Sinton *et al.*, 2020).

2.2.3.3 Maize

Maize (*Zea mays* L.) is an annual monocotyledonous cereal from the *Poaceae/Gramineae* (grass) family. It requires warm temperatures to grow, but is highly adaptable (Badu-Apraku & Fakorede, 2017). It has a high metabolisable energy and is relatively easy to grow (Eckhoff & Paulsen, 1996). It is not a complete food, lacking certain amino acids, but it is a global staple. Broadly, maize grain is used to produce starch, oil, maize gluten, cornflour, grits and alcohol. Other common processed foods derived from maize are sweeteners and syrups, cornflakes, tortillas and corn chips (Booker, 2009; Munck, 2009).

In New Zealand, the Foundation for Arable Research (FAR) is the industry research body providing core research, market data, contract standards and agronomy leadership. Maize research and dissemination is funded by a levy on the sale of maize seed (Foundation for Arable Research, 2022). DairyNZ is an important player in the industry as it represents dairy farmers who use the majority of New Zealand's maize silage produced. As many dairy farmers produce their own silage, rather than purchasing

it, DairyNZ provides guidance, resources and expertise on production, storage and feeding of silage (DairyNZ, 2025).

2.2.3.3.1 Maize production

Globally, maize is a staple crop for human consumption (FAO, 2024). In New Zealand, it is predominantly grown for stock feed rather than human consumption (Booker, 2009). In New Zealand, maize grain is used in the food industry as well as for livestock feed (predominantly poultry as well as pig, ruminant and calf). Some New Zealand hybrids are predestined for either grain or silage, but most can be used for either purpose. Booker (2009) reported that the dairy industry was responsible for the use of 99% of New Zealand's maize silage production. The Arable Industry Marketing Initiative uses data from survey farms and agricultural production statistics to estimate national production of maize grain and silage. The majority of New Zealand maize production is destined for silage (1,389,298 t DM in the 2024-2025 season) as opposed to grain (210,644 t DM for the 2024-2025 season). The average yield in the 2024-2025 season was 12.5 t DM/ha for grain on 16,801 ha and 22 t DM/ha on 62,281 ha for silage (Arable Industry Marketing Initiative, 2025). These figures demonstrate maize production is very common – the total land area for all fresh fruit and vegetable production was reported to be 74,286 ha in 2025, while the total land area for maize production around the same time was 80,802 ha (United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025).

The Arable Industry Marketing Initiative (2025) reported grower comments on the 2024-2025 season. According to growers, the price for maize grain is too low, has not changed much over the past 15 years, and this may be due to alternative feed crops undercutting the price for maize grain. In addition to the perceived low price for grain, the cost to grow it has increased.

2.2.3.3.2 Maize growth

Maize's growth habit is upright with a single stem. Plants can grow up to 4 m depending on the conditions and variety, with New Zealand varieties usually >2 m. A single, large-bladed leaf is present at each node on the stem. These alternate up the stem in two opposing rows (distichous arrangement). Maize is a wind pollinated plant. Its narrow upright habit allows many plants to be grown in close proximity, the advantage being that large quantities of pollen can be dispersed to the female inflorescences as the male flowers mature, ensuring cross pollination (Badu-Apraku & Fakorede, 2017). Maize produces two kinds of flowers – male and female, predisposing it to cross pollination.

The male inflorescence (the tassel) is produced at the top of the plant and typically matures a few days before the female inflorescence (the ear) (Vollbrecht & Schmidt, 2009; Badu-Apraku & Fakorede, 2017). The female inflorescence grows about halfway down the maize plant stem, forming from a modified spike in the axil of one of the leaves. The female inflorescence is protected by leaves that tightly surround it and form the husk. Kernels are formed from pollinated flowers and ovules. Silk extrusion indicates female flower maturity. The silks are the elongated style of each flower and are hollow tubes. Millions of pollen grains from each mature male flower are released over a period of about one week. Pollen deposited on the silks germinates, each forming a pollen tube that enters an individual silk and grows towards the ovule from the same flower to fertilise the egg and form a zygote. From this point, it takes about eight weeks for development and maturation of the grain kernels (Badu-Apraku & Fakorede, 2017).

Maize produces a few different kinds of roots. The first are embryonic roots: the primary root and seminal roots which are endogenous i.e. they from within the seed/embryo. They are the first roots formed when the seed germinates and seedling grows. Their purpose is nutrient and water uptake. During early development, they are the dominant roots. Postembryonic root development includes the lateral roots formed from the primary and seminal roots. These are short branches off the existing primary and seminal roots. They also include two types of shoot borne roots. The first are the crown roots. These develop at the base of the plant, above the seed/embryo but below ground level. The other kind of postembryonic roots are the brace roots. These thick roots form from the bottom two to three nodes that encircle the stem and grow down into the soil. Their function is anchorage (Hochholdinger, 2009).

2.2.3.3.3 Maize pests and diseases

Like many crops, maize is susceptible to a number of pests and diseases at different stages of development. Australian soldier fly, wireworms, weevils, black beetle, Argentine stem weevil, greasy cutworm, Cosmopolitan army worm, Southern army worm, corn ear worm, green looper, cereal aphid, corn leaf aphid, maize seed beetle and slugs are invertebrate pests that have been recorded to attack maize in New Zealand (Watson & Hill, 1984). Maize is also susceptible to fungal, bacterial, viral and mycoplasm infections. In the past, northern leaf blight, head smut, ear rot and root rot caused economic impacts on crops (Fowler, 1984).

2.2.4 Issues around food production

2.2.4.1 Disconnect between production and distribution

According to Fraser *et al.* (2016), global food production is sufficient to meet the energy needs of the current and growing population. However, due to inefficiencies in production and distribution systems, global food per capita is unequal (Mc Carthy *et al.*, 2018). In fact, it is so unequal that in 2022, the World Health Organisation reported there were more overweight (43%) and obese (16%) than healthy and underweight people >18 years old (World Health Organization, 2025). Putting the issue of distribution aside, it cannot be assumed that food production will remain sufficient for a growing population under the threat of climate change (Foley *et al.*, 2011) and environmental degradation. Therefore, efforts to meet the food energy demands of a growing population should include (i) improving availability e.g. via efficient distribution and reduced organic/food waste, and (ii) increasing total food production, food quality and farm system resilience (Foley *et al.*, 2011; Fraser *et al.*, 2016).

2.2.4.2 Environmental impact

Importantly, environmental health needs to be an integral part of future food production. Commercial food production depends on environmental health. Environmental health directly impacts soil and water resources and consequently has an impact on climate change (FAO, 2021). Direct environmental consequences of agricultural production include greenhouse gas (GHG) emissions, soil erosion, nutrient runoff and leachate from soils to waterbodies leading to eutrophication, decline in soil organic carbon (SOC), biodiversity loss, and soil, water and air quality degradation (Sharpley *et al.*, 1994; Foley *et al.*, 2011; Mc Carthy *et al.*, 2018; Gallardo, 2024). Climate change has already impacted food production (FAO, 2021) and preparations need to be made to meet the challenges these changes pose.

As well as researching the environmental impacts of production, authors are also investigating the environmental impacts of dietary nutrition in New Zealand (Barnsley *et al.*, 2021; Curran-Cournane & Rush, 2021; McDowell *et al.*, 2024). Shifts in diets can influence the sustainability of food production (Fanzo *et al.*, 2018).

On a per kilogram basis, unprocessed fruit and vegetable products have a lower environmental footprint than meat and meat products (Tilman & Clark, 2014). However, when processing is factored in, meat and meat product production can have a lower environmental footprint. However, these trends depend on the product and production

system in question e.g. tomato crops grown in a heated glasshouse and animals grazed on pasture vs fed in housing facilities (Barnsley *et al.*, 2021; Ledgard, 2021).

Agriculture has become more intensive over time due to increased demand, improvements in efficiency and new technologies. Because of this, less land is needed to produce the same quantity of food, however this has in turn led to accelerated environmental degradation (Bruinsma, 2009). This fits Jevons Efficiency Paradox where resource efficiency is increased and production costs are decreased, but total consumption of the resource increases due to increased demand, production and consumption. Without a form of control such as policy to restrict the extent of certain activities, resources can be exploited in a manner that harms the environment (Hamant, 2020). It is unfortunate that a path intended to enable efficiency can have the opposite effect when appropriate controls are not implemented.

2.2.4.3 Land availability and regulations

Non-agricultural factors affect land use and the security of agricultural production. Urban expansion and land fragmentation are reported as key drivers of the loss of productive land in New Zealand (Ministry for the Environment & Stats NZ, 2024). While not a policy, this kind of restriction on land suitable for horticultural activities limits expansion as land developed for housing irreversibly changes soil properties and is permanently unavailable for food production.

New Zealand's land is divided into eight categories of Land Use Capability (LUC) depending on its "long-term capability to sustain one or more productive practices". Class 1 and 2 soils are the most versatile and productive soils and are considered finite national assets (Lynn *et al.*, 2009; Rutledge *et al.*, 2010). Given New Zealand's reliance on its ability to export primary produce, such soils should be valued highly. Data from 1970-1990 showed that Class 1 soils made up 0.7% and Class 2 made up 4.5% of New Zealand's total land area. Class 3 can support vegetable production (9.2%) but requires more management. Loss of productive land means that to be able to maintain or increase production, other crops may need to be grown, or production shifted to soils in other LUC classes that require more intensive and expensive management. There is a finite amount of versatile and highly productive land available in New Zealand, meaning that this amount can either remain stable or decline (Rutledge *et al.*, 2010). According to Ministry for the Environment reports, New Zealand's highly productive land (14% of total land area) is at risk of development due to anticipated population growth through urban expansion. Conversely, to increase wealth through industry and government goals of

increased production, agriculture (including horticulture) is expected to intensify and this will increase pressure on the environment, including soil health, water quality and indigenous biodiversity (Ministry for the Environment & Stats NZ, 2024).

Under the Resource Management Act 1991 (RMA), soils are managed as part of an integrated framework governing land, air, and water to promote sustainable resource use. A lack of sufficient housing for the current and growing New Zealand population as well as the need to provide land for further housing and business development resulted in the introduction of the National Policy Statement for Urban Development 2020 (NPS-UD). This NPS promotes the development of urban areas, but does not provide protection of highly productive land (nor greenfield areas around urban zones) (Ministry for the Environment, 2022). A few years later, the National Policy Statement for Highly Productive Land 2022 (NPS-HPL) was introduced to ensure that New Zealand's most versatile and productive soils are protected for ongoing food and fibre production. Together, the RMA and NPS-HPL guide councils in managing soil resources and safeguarding highly productive land from inappropriate subdivision, use and development (Ministry for the Environment, 2025b). Under the NPS-HPS, Councils are required to map the areas of highly productive land in their regions and have until the end of 2027 to do so. However, as of December 2025, urban development and rezoning on Class 3 land in greenfield areas around urban zones were exempted from the NPS-HPL restrictions to make more land available for housing. This change has been made as the NPS-HPL was seen to be too restrictive on urban development, compounding the current housing crisis (Ministry for the Environment, 2025a). Clause 3.6 of the NPS-HPL does allow rezoning of highly productive land if there will be significant benefit to the NPS-UD i.e. the benefits of rezoning will outweigh the cost of productive land loss and there are no other practicable and feasible options (Ministry for the Environment, 2025b). At the time of writing, the intentions of both developing land to alleviate the housing crisis while protecting finite reserves of productive soils appear to clash here as highly productive land is often located on the fringes of urban areas (Ministry for the Environment & Stats NZ, 2021). In December 2025, Central Government introduced two new Bills to replace the existing RMA. These are the Planning Bill that regulates how land can be used and developed and the Natural Environment Bill that regulates the use of natural resources and protecting the environment. This is a change from case-by-case approval of activities under the RMA to nationally directed strategic planning with the intention of balancing development with protection of national assets. However, as

Class 3 land around urban areas has already been exempted from the current NPS-HPL restrictions, New Zealand's finite highly productive soil resources will continue to decline.

The relevance of the regulatory topic for this thesis ends here, however, it was important to include this context as it highlights that the limited amount of highly productive land available is finite and under threat from other land use activities.

2.2.4.4 Climate change and weather extremes

Food production is also at risk of extreme weather events, such as recently seen in 2023 when Cyclone Gabrielle hit the Gisborne region, economically impacting growers, causing farmgate returns to drop by $440m (United Fresh New Zealand Incorporated & Bioeconomy Science Institute, 2025). Climate change, accelerated by anthropogenic activities, is a threat to food production. Rising CO_2 levels in the atmosphere may act as a fertiliser and be beneficial for the quality of some crops, but have negative implications for others (Bindi *et al.*, 2006; Fanzo *et al.*, 2018). Rising temperatures associated with elevated CO_2 exacerbate weather extremes such as droughts, floods and high winds (FAO, 2021). Changes in climate also affect pest and disease pressures, likely allowing southward migration of pests in New Zealand, following their preferred climate conditions and changes in crop dispersal (Gerard *et al.*, 2013).

2.3 Soils and nutrients

2.3.1 Soil health

Soils are ecosystems and their health cannot be defined by individual indicators. The definition of soil health is not fixed. Defining soil health needs to include ecosystem health and functioning, though their ability to benefit human health is also included (Lehmann *et al.*, 2020). Major ecosystem services provided by soils include biodiversity (Fitter *et al.*, 2005), plant production, water quality control, human health advancement, and climate change mitigation. These are all important factors for agricultural production (Lehmann *et al.*, 2020). In New Zealand, most regional councils are monitoring soil health using seven key quality indicators grouped into four categories: Olsen P (indicating fertility through a chemical measure of phosphorus availability), pH (acidity influencing how hospitable a soil is for plants and soil biota as well as nutrient availability), physical status (bulk density and porosity) and organic reserves (indicating how much organic material is available for providing nutrients and soil structure, measured through total carbon, total nitrogen and mineralizable nitrogen) (Ministry for the Environment & Stats NZ, 2018).

Soil types vary with geographic location, age and developmental processes. New Zealand soils are considered geologically 'young' compared to Europe, North America and Australia (Kirkman *et al.*, 1994) but have many desirable properties that are beneficial for agriculture (Lynn *et al.*, 2009). Agriculture impacts soil quality as well as the environment (Sparling & Schipper, 2004; Gallardo, 2024). According to Sparling and Schipper (2004), compared to indigenous forest soils, soils that have been used for pasture, forest production or horticulture/crops, productive soils (in this context, these are those that have been used for production) were more likely to be outside soil quality target ranges for nutrient status. For cropping soils, loss of organic matter and moderate compaction was a concern. Fallow periods (where soils are left bare i.e. no crops are grown) and cultivation both reduce soil organic matter content. This can be compounded by the addition of wind and water erosion on soils in an unprotected state (Rasmussen & Collins, 1991). Cultivation and crop rotation also affect soil biota, including earthworm populations (Francis & Knight, 1993; Wright *et al.*, 2015). Although an effect of cultivation is an increase in the size of aggregates (clod formation), the process immediately breaks open soil aggregates, allowing microbes access to organic matter that was previously inaccessible as it was physically protected (Golchin *et al.*, 1998; Janzen *et al.*, 1998; Shepherd *et al.*, 2001). Organic matter addition to soils is known to improve plant production (Blouin *et al.*, 2019). Loss of soil organic matter affects soil functioning. Soil organic matter binds soil aggregates, holds moisture and nutrients and provides food for soil biota. The advantages of cultivation include the provision of an even, fine tilth for seed-soil contact and the flush of mineralisation and subsequent nutrient availability as well as mixing of nutrients and soil carbon. Weed control is another benefit of cultivation (Dimassi *et al.*, 2014; Mühlbachová *et al.*, 2024). In the short term, cultivation can boost crop yields (Carey *et al.*, 2023), however, repeated cultivation is recognised to have a detrimental effect on soil organic matter and therefore soil health, though allophanic soils appear to be more resilient to the detrimental effects of cultivation on soil organic matter (Shepherd *et al.*, 2001).

2.3.2 Fertilisers

Being major plant nutrients, nitrogen (N) and phosphorus (P) are the most commonly applied nutrients in fertilisers. However, they are also the most commonly reported nutrients causing damage in other environments (Sharpley *et al.*, 1994; Abell *et al.*, 2010; Abell *et al.*, 2019). To maintain/increase production from harvested land, fertiliser is applied because exported products such as horticultural products, dairy and

wood contain nutrients that are removed from soils and transported overseas in these products. As these nutrients are not returned to productive soils, nutrients must be imported from other sources to replace what has been removed. In 2019, New Zealand's fertiliser use was estimated at >220,000 t P and >1,180,000 t nitrogen (N) applied across all farm types (Stats NZ, April 15, 2021).

The primary form of N applied to agricultural land in New Zealand is urea. There is one urea manufacturing plant in Taranaki, New Zealand (Ballance, n.d.), though it does not produce all urea used in New Zealand.

New Zealand soils tend to be deficient in available phosphorus (P) – some soils such as allophanic soils of volcanic origin have a high P-fixing capacity (Kirkman *et al.*, 1994). In addition to the large quantity of agricultural products being exported, P must be reapplied to soils to maintain production (Fertiliser Association, 2021). Rock-phosphate is a non-renewable resource imported into New Zealand as a raw form of P for agriculture. The majority (70%) of rock phosphate imported to New Zealand comes from Western Sahara (Fertiliser Association, 2021).

2.3.3 Phosphorus

Phosphorus is non-renewable resource, essential for life. Almost all of the global demand for rock phosphate is for food production. In nature, the phosphorus (P) cycle is a closed cycle, but due to anthropogenic intervention, the cycle is out of balance so globally, the P cycle acts more like a linear process. Anthropogenic consumption patterns tend to lack the recycling and reuse of P, making P use in food production inefficient. The world faces a dual crisis of widespread P pollution and impending rock phosphate scarcity. Rock phosphate has been the primary source of P used in agriculture for decades. It is a non-renewable source of P. Phosphorus continues to be harvested from non-renewable sources and used inefficiently, worldwide (Cordell *et al.*, 2009).

In New Zealand, superphosphate is the most commonly applied form of P fertiliser (Ballance, n.d.). It is produced by Ballance Agri-Nutrients and Ravensdown by dissolving rock phosphate in sulphuric acid to convert the insoluble phosphate rock into a plant-available form mono-calcium phosphate. Calcium sulphate is another fertiliser compound formed in superphosphate production – a desirable addition as New Zealand soils are naturally low in sulphur. Since 2014, almost 60% of New Zealand's rock phosphate imports have come from Morocco, with China, South Africa, Togo, Vietnam, Australia/Christmas Island, Nauru, Peru, Egypt and other countries supplying the remainder. Fertiliser imports have been reducing as profit margins are declining due

to increased interest rates and lower farm gate returns. In 2022, 645,781 t rock phosphate were imported to New Zealand (USDA & GAIN, 2023).

Multiple factors such as parent material, soil type and texture (fixed), and metal oxides, soil pH, salinity and organic matter content (changeable) contribute to the complex cycling of phosphate in soil (Billah *et al.*, 2019). Phosphate ions such as from the application of superphosphate fertilisers bind chemically to the surface of soil clay minerals and iron and aluminium oxides such as allophane and organic matter. When this happens, they become inaccessible to plants (Bolan, 1991) unless conditions change and the P is released e.g. mineralised from organic matter (Chauhan *et al.*, 1979). Olsen phosphorus (Olsen P) is an estimate of available P in soils. It is measured by extracting phosphate ions with sodium bicarbonate at a pH of 8.5 (Olsen *et al.*, 1954).

The Ministry for the Environment and Stats NZ (2021) reported Olsen P levels in test sites for nine different land uses between 2014. Of the 628 sites sampled between 2014-2018, 61% cropping land, 61% dairy, 30% drystock, 11.8% exotic forestry, 16.7% lifestyle, 45.6% orchard/vineyard, and 13.9% urban park/reserve sites had Olsen P levels higher than the target range, with dairying on volcanic soils having the highest target concentration of 50 mg Olsen P/kg soil. The average concentration for dairying was 67 mg/kg. In the previous reporting series (1996-2018), it was reported that cropping soils and drystock land both had increasing Olsen P levels. This report indicates that in many cases phosphorus (P) has been over-applied (Ministry for the Environment & Stats NZ, 2018). Excess P is at risk of leaching and causing damage to other environments e.g. freshwater ecosystems, aquifers and estuaries (Cordell *et al.*, 2009).

This imbalance needs to be addressed through significant changes to farming practices and management of P (Cordell *et al.*, 2009). Phosphorus has already exceeded planetary boundaries for freshwater eutrophication (Carpenter & Bennett, 2011). Changes to farming practices should include shifting from reliance on rock phosphate and its derivative P fertilisers to cycling P efficiently within food production and processing systems, with particular focus on organic waste recovery.

According to (Cordell *et al.*, 2009), globally P use is very inefficient with five times more P being mined than consumed in food. In regard to the availability of rock phosphate as a fertiliser source, using less/achieving the most efficient use is not enough. This is a finite resource and using it more efficiently, for example, consuming all of what is mined, will not solve the scarcity issue. Trying to use rock phosphate as efficiently as possible will merely result in slower depletion of this non-renewable resource, while still causing environmental damage (McDonough & Braungart, 2002). The impending P crisis

requires a different solution to sourcing more deposits of rock phosphate. Some creativity is needed in the design of our agricultural systems and find renewable sources of P, while managing these systems to also minimise P losses. Alternative sources of P already exist: (i) organic wastes and (ii) excessive P levels already in agricultural soils (Legacy P). Legacy P is considered to be a long-term source of (water) soluble P for agricultural soils (Roswall *et al.*, 2021). However, legacy phosphorus is not a focus of this research so it is not discussed further.

2.3.4 Alternative N and P

Not all organic wastes should be considered 'waste' products. Instead, they can be seen as *resources*. Economic, social and environmental aspects need to be taken into account when determining the best option for management of organic resources (Blouin *et al.*, 2019). Chicken litter is an example of an alternative source of N and P.

2.3.4.1 Production of chicken litter

The poultry industry includes (primarily) chickens, ducks and turkeys and includes layers (for eggs) and broilers (for meat). Poultry manure is a by-product of the layer industry. Chicken litter is a by-product of the broiler (meat) industry. Chicken litter consists of wood shavings/bedding material, manure and spilt feed. Turkey and duck manure is not included due to the relatively small size of these industries. Large quantities of litter are produced by the poultry industry (an estimated 225,657 t fresh litter from 120 million broilers in 2022) (PIANZ & EPFNZ, 2012; PIANZ, 2022). This material is refreshed at each new placement of birds – approximately six times per year in broiler farming and approximately once per year in layer farms. On large layer farms, manure is continually removed from layer systems by conveyor belts and hens are kept in caged facilities with limited access to litter-lined areas, hence litter is refreshed less often. In the broiler industry, used litter is immediately removed from the farm by contractors – usually a fertiliser company. Mortalities (carcases) are removed by hand before the litter is taken from the shed. Mortalities are collected during the growing or production period and collected for composting or rendering. Small farms may compost or bury mortalities. Large farms, including all broiler farms, have a defined process of collection, holding in coolers/freezers and then sending mortalities away for rendering or composting. This is to avoid the spread of disease on pastoral farms via direct contact of the carcass with ruminants. Carcasses are usually disposed of in offal holes, if permitted, or buried. In the layer industry, manure is continually removed from the sheds via conveyor belts. While travelling through the shed on the belts, it is air-dried by the shed's ventilation system.

The dried manure is then deposited in bags or bins before being carted away by a contractor. Due to lack of space, odour emissions and the risk of harbouring pathogens near other poultry sheds, the litter is not treated or stockpiled on the farm. Once past the farm gate, the disposal of the litter is the responsibility of the contractor and end-user who directs the application (Kerry Mulqueen, personal communication, November 11, 2022).

The composition of chicken litter is variable. Being an organic material, actual nutrient contents vary between batches and depending on factors such as whether the material has been stockpiled or is applied fresh (Bolan *et al.*, 2010).

2.3.4.2 Management of chicken litter

Chicken litter is as a nutrient-rich organic fertiliser usually applied directly to land. Improper handling, storage and land application of chicken litter results in excess nutrient losses and odour production (Bolan *et al.*, 2010). Industry records of poultry litter collection and management are not well reported. In New Zealand, it is estimated that the majority of chicken litter is applied to pasture, with only a small fraction being composted. Around 2010-2012, it was estimated that 3-4% of poultry manure in New Zealand underwent intensive composting (PIANZ & EPFNZ, 2011, 2012), however this figure is not well referenced, and it is uncommon for composting to occur nowadays (Graeme Rodley, personal communication, November 4, 2022) (PIANZ & EPFNZ, 2011, 2012; PIANZ, 2022). There is conflict between reports on the management of chicken litter in New Zealand. This may be due to changing practices over the past decade, however there are no clear standards for chicken litter management in New Zealand. Even management practices such as standdown periods after application do not fit with food safety standards recommended for application in horticulture – there is a lack of connection between producers, distributors and end users.

A report by PIANZ and EPFNZ (2012) stated that “in NZ all poultry manure undergoes a stand-down of 14–21 days before land application”. However, a more recent report prepared for the Ministry for Primary Industries indicates that chicken litter from broiler farms is applied fresh as “broiler litter is normally taken directly from the sheds and spread on land the same day” and manure from layers is “typically scraped to a storage bunker and collected until enough volume has accumulated before it is carted away as hen (or poultry) manure for land application” (Luo *et al.*, 2019). Neither report indicates how long stockpiles may remain static before being land applied. In addition, there is a paucity of information on industry standards and best management practices.

Management of chicken litter may soon come under regulation in New Zealand due to the current lack of standards, increase in poultry production and the environmental and health risks associated with the management of litter and manure. In 2005, Standards New Zealand released voluntary guidelines for production and testing of composts, soil conditioners and mulches (Standards New Zealand, 2005). While not written specifically for chicken litter management, these standards can be followed to produce a quality, compliant compost.

According to reports from 2010 and 2012, the majority of chicken litter produced in New Zealand used to be applied to pasture (PIANZ & EPFNZ, 2011, 2012). Since these reports were published, demand and use of chicken litter have changed, with the majority now being applied during maize cropping (pre-sowing to ensure incorporation into the soil, partly to minimise odour) (Graeme Rodley, personal communication, November 4, 2022).

2.3.4.3 Use of chicken litter as an alternative source of N and P

Synthetic urea fertiliser prices and poultry manure use are linked to the price of oil (PIANZ & EPFNZ, 2012) (Kerry Mulqueen, personal communication, November 11, 2022). When the price of oil is high, chicken litter increases in popularity. Higher oil prices result in higher manufacturing costs e.g. for synthetic N fertilisers. Chicken litter then becomes a more attractive option for farmers and has the added benefits of other nutrients such as phosphorus (P) and the addition of organic matter and beneficial microbes to promote soil health and function. Its use is also not restricted under the Synthetic N Cap that came into effect in July 2021 (Ministry for the Environment, October, 2021). Supply of litter would also be affected by poultry farmers choosing to reuse litter at least for one more cycle per year. On average, there are six cycles per farm, per year. This could potentially result in three batches of used litter being produced per year. A more nutrient-dense chicken litter would be produced at the end of the litter's life. This would likely be a more fertiliser product with a higher nutrient value, however there would likely be greater odour and environmental emissions than single-use litter.

Litter is produced all throughout the year. Most litter spreading occurs during spring and the majority of this is land-applied to pasture or crops (mainly maize) (Graeme Rodley, personal communication, November 4, 2022). Winter spreading is not recommended due to the high mineral and mineralisable nitrogen (N) content of the litter and the difficulty in getting heavy machinery such as muck-spreaders on soil without damaging its structure. In addition, the addition of water to chicken litter/manure

increases microbial activity which can give rise to very offensive malodorous gases such as ammonia. Furthermore, it is often recommended to incorporate litter/manure into soil to minimise odours and this is usually not possible in winter. Excess litter is therefore often stockpiled by the contractor company to fill orders in spring.

Spreading also does not tend to occur in mid-summer as it is usually too dry for crops/pastures to receive nutritive benefits. This is also the middle of the growing season for many crops so tillage to incorporate the material is impractical (Graeme Rodley, personal communication, November 4, 2022).

2.3.4.3.1 Risks of poultry by-products

Commercial poultry farms are unable to process chicken litter *in situ* within their own farm boundaries. Environmentally, it is unfeasible for nutrients in the litter to be cycled on such small areas of land. For example, chicken litter's P content alone is too high for repeated land application (Bolan *et al.*, 2010). Fresh chicken litter has a higher rate of N mineralisation than litter that has been processed/stabilised in some way e.g. via composting. This means there is a greater risk of N leaching from fresh litter applied to land (Bolan et al., 2010). Poultry farms are therefore reliant on other industries to utilise their untreated by-products (Kerry Mulqueen, personal communication, November 11, 2022; Graeme Rodley, personal communication, November 11, 2022).

Both the management and use of poultry by-products (such as litter) pose health risks. According to Fresh Produce Safety Centre Australia & New Zealand (2019) microbial contamination of food crops e.g. *Salmonella* and *Escherichia coli* can occur from both direct and indirect contact between materials containing untreated manure and harvestable produce. This can even occur with composted[2] poultry wastes.

Chicken litter is a suitable material for composting – it readily undergoes thermal decomposition. Chicken litter adds plant nutrients and can improve soil structure, but in an untreated form (fresh or stockpiled, not thermally composted) chicken litter can pose a food safety risk by contaminating fresh produce through direct indirect contact. Cross-contamination with unsanitised products can be caused by machinery, wind and water. Environmental conditions like flooding can also transfer pathogens onto produce. Climatic/environmental conditions can also perpetuate the longevity of the pathogens in

[2] Note that the definition of 'composted' manure is not explained here i.e. whether the material meets the Standards New Zealand (2005) standards for composts. Properly/fully composted chicken litter should not pose a food safety risk of pathogen contamination. However, at the time of writing this thesis, it was not industry standard to fully compost chicken litter before application to soils in New Zealand e.g. to comply with the voluntary NZS 4454:2005 composts, soil conditioners and mulches guidelines.

the soil and on the produce after application (Fresh Produce Safety Centre Australia & New Zealand, 2019). To minimise the risk of pathogen contamination via manure application, recommendations include (i) avoiding applying untreated manures to soils/crops, and (ii) observing an appropriate exclusion period between manure application and crop harvest.

2.4 Other organic wastes

2.4.1 DAF sludge

2.4.1.1 Production of DAF sludge

In the broiler industry, hatched chicks are processed for human consumption at about six weeks of age. The approximately 120 million broilers produced annually in New Zealand are processed at specialised facilities where both meat products for consumption and by-products are produced (PIANZ, 2022). Some by-products can be sold to alternative markets such as heads for petfood and feet for human consumption. Solids such as guts and yard waste can be rendered for fat and petfood (Artika Devi, personal communication, July 15, 2025). Large volumes of effluent generated during meat processing need to be treated before discharge to the environment. Effluent has polluting characteristics such as high nutrient loads, biological and chemical oxygen demand and suspended solids. The dissolved air flotation (DAF) process tends to be a primary treatment process for processing plants. The aim is to remove fats, oils, grease, residual total suspended solids (TSS), biological oxygen demand and chemical oxygen demand. According to Metwally (2026), there are four key steps in the DAF process: (i) generation of air bubbles in the wastewater, (ii) adherence of air bubbles to small particles suspended in the water, (iii) flotation of solid particles via the air bubbles to the surface where (iv) they can be skimmed off as a solid component (DAF sludge).

A case study primary processing poultry plant was visited in July 2025 for a tour of their wastewater treatment facilities[3]. A diagram of the process is presented in Figure 2-1. The plant discharges treated effluent to a company-owned dairy pasture in summer (November to April), or an estuary in winter (May to October). There are daily limits for application according to their resource consent. The solid component of the wastewater treatment process (including DAF sludge) is discharged onto separate paddocks. The greatest concern with effluent discharge is nitrogen. To reduce the risk of N losses to the environment, soil moisture is monitored before land application. The farm has a policy of

[3] Note that the DAF sludge used in the Chapter 3 experiments was not obtained from this plant.

a 6–8-week stand-off period before grazing or reapplication of effluent/sludge can occur (Artika Devi, personal communication, July 15, 2025).

Dissolved air flotation sludge at this site is produced at the final stage of wastewater treatment (Figure 2-1, though disposal of the solid DAF sludge component is not included in this diagram). The purpose of the DAF plant is to clarify the wastewater, by reducing TSS in the final effluent. Both a coagulant and a polymer flocculant are dosed into the DAF plant as the wastewater is cycled through it. The coagulant is dosed directly into the DAF plant to neutralise electrically charged particles. The flocculant is diluted in a dosage tank to achieve the minimum desired concentration (based upon TSS in the Sequence Batch Reactor; SBR) prior to dosing the wastewater as it flows into the DAF plant. Wastewater is continuously pumped into the DAF plant from the SBR. As a preventative measure, TSS is monitored in the SBR and the coagulant + flocculant concentrations can be adjusted to compensate if needed (Artika Devi, personal communication, July 15, 2025).

In general, the DAF process involves the addition of a chemical flocculant to cause solids to flocculate into larger particles. These particles are floated to the surface of the DAF plant through fine streams of air bubbles. The solids can then be scraped off the surface of the water, leaving behind a clearer wastewater effluent (lower TSS). The DAF sludge can contain high levels of fats, oils and grease, and have high moisture and nutrient contents.

2.4.1.2 Standard management of DAF sludge

According to Westerman *et al.* (1989), biosolids such as DAF sludge from poultry processing have been landfilled or rendered in the past. However, the high moisture content, odorous nature and polymer/chemical content of the sludge has resulted in rendering plants tending to reject chicken DAF sludge as an input. Landfills are also reducing their acceptance of wastes, including DAF sludges so land application is the most common method of sludge disposal (Westerman *et al.*, 1989). Dissolved air flotation sludges from other sources such as dairy processing can be used as non-ruminant feed e.g. for pigs. According to the Biosecurity (Meat and Food Waste for Pigs) Regulations 2005, Chicken DAF sludge is unacceptable as an animal feed for pigs as it contains meat waste. In a Guidance Document for disposal for dairy DAF sludge, the Ministry for Primary Industries also reports that both landfilling and the application of DAF solids to land as either a soil conditioner, input for worm farming or composting or surface/subsurface application are considered disposal (Ministry for Primary Industries, 2021). DAF tends

to be too wet for rendering and too fatty for anaerobic digestion (Westerman *et al.*, 1989). Shanmugam *et al.* (2025) showed that poultry DAF can be processed using black soldier fly larvae, but the outcomes were much better if the DAF was mixed with food waste.

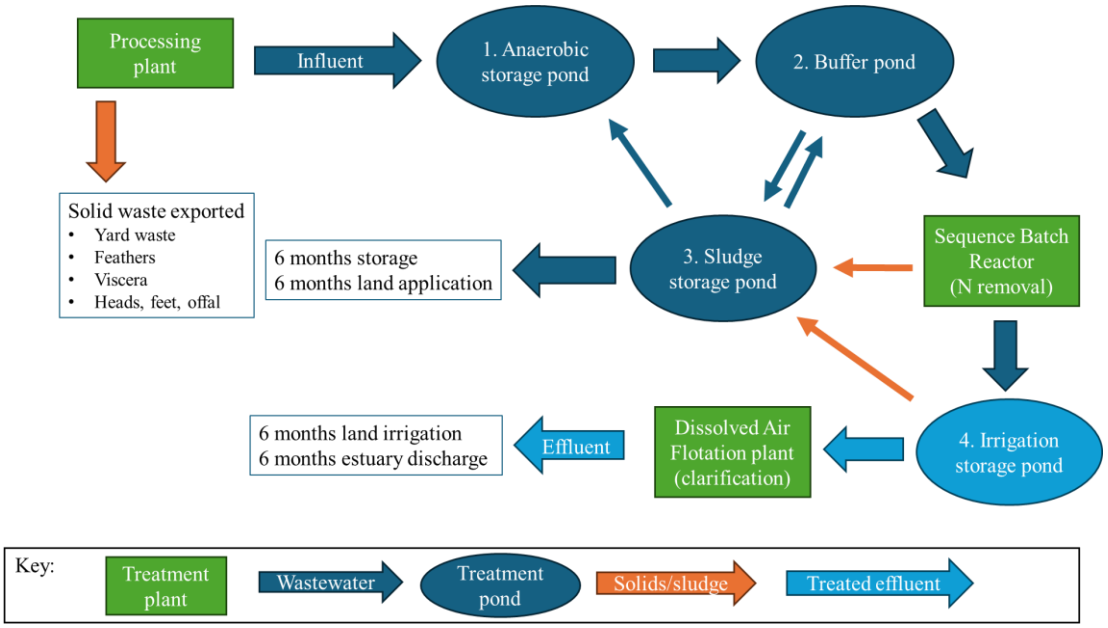


Figure 2-1: Case study wastewater treatment process – effluent production (Artika Devi, personal communication, July 15, 2025).

In a study by Westerman *et al.* (1989), a N mineralisation trial of chicken DAF sludge from two sources incubated in two soils showed that organic forms of N become quickly available, first as NH_4^+ then later as NO_3^-. Initially, there was a spike in NH_4^+ content, but this was then converted to NO_3^- through the process of nitrification. The authors reported nitrification began within a week of incubation for the first soil, but there was a delay of four weeks in the second soil, which had been adjusted for pH prior to incubation. This trial demonstrates that DAF sludges vary, as does their N supply. However, doubling the sludge Total Kjeldahl Nitrogen (TKN = organic N + NH_4^+-N) application rate nearly doubled final NO_3^- levels after 24 weeks, regardless of the DAF source. The second experiment conducted by the authors showed that DAF sludge applied to corn plants was less effective at increasing dry matter (DM) yield than chemical NH_4NO_3 fertiliser. Nitrogen application rates were not balanced between the treatments, with the fertiliser N application rates lower at 160 and 240 kg N/ha and DAF applications at 288, 432, 576 and 720 kg TKN/ha. The DAF applications are reported in TKN, which accounts for most N, but not NO_3-N. Total N includes all components. Given their first experiment showed that NO_3-N content was initially very low, the TKN results may actually be close to TN (unmeasured). However, the N applications from the DAF sludge were still much greater than the fertiliser N applications. Much of the additional N in the

DAF sludges over that supplied by the fertiliser treatments was unavailable. The additional N load of the DAF sludge reduced the agronomic N efficiency (yield increase per unit of N applied) as there was a greater supply of N, though only a fraction of the DAF sludge N would have been mineralised within the corn's growth period.

These experiments highlight the risk of N losses to the environment from DAF sludge applications. The first experiment shows that substantial quantities of NO_3^- can be produced. The second experiment shows that if plant available N supply is not synchronised with plant N demand, losses to the environment could become an issue. The low short-term availability of N supplied by the DAF sludge could mean more N left in the system for loss if plant uptake declines with age.

2.4.2 Paper waste

2.4.2.1 Production of paper waste in New Zealand

There is a high demand for production and consumption of paper products in New Zealand. In 2015, 144,000 t newsprint, 31,000 t tissue paper and 546,000 t packaging and industrial paper waste was produced in New Zealand (721,000 t total). Of this, 92,500 t newsprint, 30,400 t tissue paper and 199,400 t packaging and industrial paper was sold locally (64%, 98% and 37% of 2015 production, respectively) (IndustryEdge, 2022). This is a total of 322,300 t locally produced paper for consumption in New Zealand. In 2018, it was reported that 480,000 t paper is received by the recycling industry in New Zealand. This indicates that imported material is added to New Zealand's recycling system (IndustryEdge, 2022). According to the Ministry for the Environment website, of the annual 830,000 t of paper and cardboard products produced each year, 66% (550,000 t) is collected for recycling (Ministry for the Environment, January 24, 2024). This is a 14.5% increase from the previous 2018 estimate. However, at the time these data were published, New Zealand was recycling almost half its own paper and cardboard. Since then, the largest paper recycling plant in New Zealand (Oji Fibre Solutions, Penrose Mill), with a capacity of approximately 100,000 t/year has closed down. Collected recycling that used to be processed locally is now exported. The cardboard recycling plant at Kinleith (also owned by OjiFS) remains operational, processing around 90,000 t/year (OjiFS, 2024).

Guidelines for kerbside recycling for residents and businesses are provided to minimise contamination. Food containers can be recycled, provided they are not contaminated with food e.g. pizza boxes with food adhered. Large pieces of plastic are required to be removed. Specific items that cannot be recycled in New Zealand are drink

cartons e.g. Tetra Pak cartons, cardboard tubes for chips e.g. traditional Pringles cans, takeaway coffee cups, waxed cardboard, foil-based gift wrapping, cards or wrapping with glitter, shredded paper, tissues and paper towels. Reasons for non-recyclability of these materials include contamination with materials like metal and plastic, small size, polythene plastic linings and contamination with food scraps and cleaning chemicals (Ministry for the Environment, January 24, 2024).

2.4.2.2 Standard management of paper waste in New Zealand

Not all paper waste is recycled in New Zealand. Some of it may be composted or vermicomposted, but the majority of non-recycled paper currently goes to landfill (Auckland City Council, August 1, 2019; Ministry for the Environment, September 9, 2021). Prior to the OjiFS Penrose Mill closure in 2024, of the total paper material received for recycling in New Zealand, 60% of this was exported i.e. New Zealand did not have the capacity to recycle all of its paper waste (Wilson *et al.*, 2018; Auckland City Council, August 1, 2019). According to the Ministry for the Environment, approximately half is recycled in New Zealand, though this information was reported prior to the closure of the Penrose Mill (Ministry for the Environment, January 24, 2024). While about half of the paper waste collected in New Zealand is destined for recycling either locally or internationally, significant volumes of paper waste that do not enter the recycling system are sent to New Zealand's landfills. In 2020, it was estimated that 218,211 t paper was sent to landfill in New Zealand (Ministry for the Environment, September 9, 2021). The reasons for this are not stated, however contamination, unsuitability for recycling/composting, and lack of sorting would be reasonable assumptions.

A vulnerability of New Zealand's paper waste processing is its reliance on overseas processing. If conditions overseas change such as was experienced in 2020 with the COVID-19 pandemic, New Zealand systems will come under significant pressure. During the Level 4 lockdown from March to May 2020, recycling was not classed as an essential service, unlike general rubbish collection. Recycling collection became sporadic, storage facilities came under pressure, facilities requiring manual sorting had to stop processing and recyclables were landfilled (The Conversation, 2020).

2.5 Organic waste management of DAF sludge

As stated earlier, chicken DAF sludge tends to be land applied without stabilisation while non-recyclable paper wastes are landfilled. There are other options for management of these organic wastes. These are anaerobic digestion, composting and vermicomposting. Having high protein, fat and moisture contents makes DAF sludge

difficult to manage as the combination make it an odorous and nutrient rich waste product. The potential risks of long-term land application include damage to soil structure through undecomposed fats and oil clogging soil pores. In addition, oxygen demand can be increased dramatically leading to anaerobic conditions in the soil that damage plants and impact yields (Simpson, 1991). However, an earlier N-balanced study showed that in a four-year study chicken processing DAF sludge produced the same corn yield as conventional fertilisers with no detrimental effects on seedling germination or groundwater quality (Carr *et al.*, 1988).

Anaerobic digestion is a process designed to produce methane/biogas. A liquid byproduct (digestate) is produced and can be used as a fertiliser. It is an ideal process for high moisture wastes such as sludges and the design of the system contains odours well. However, it is not well suited to processing paper wastes though pretreatment or co-digestion with other wastes could improve the efficiency of biogas production (Gonzalez-Estrella *et al.*, 2017). Anaerobically produced digestate has nutritive value comparable to conventional fertilisers and manures. It has also been shown to improve soil structure in the short term. However, little research has been done on the long-term effects on soil structure, and they have greater potential than livestock manures for emitting NH_3 (causing offensive odour) and N_2O (contributing to greenhouse gas emissions) (Nkoa, 2014).

Thermal composting is a common method of organic waste management with the benefit of pathogen sanitation and weed propagule sterilisation through heat treatment. Pathogen destruction begins around 50°C and depending on the species, temperatures held at 55°C for three days have been shown to destroy common pasture and weed seeds (Grundy *et al.*, 1998). The end product is a nutrient-rich, humus-like organic material (Vinnerås *et al.*, 2010). To compost sludges, a bulking material is required to provide a carbon source for decomposition, but also to absorb moisture and improve the structure, allowing air flow. This reduces the risk of anaerobic zones forming, minimising odour production (Andraskar *et al.*, 2021). A study by Alvarez *et al.* (2009) showed that only white paper and recycled paper wastes were suitable for thermal composting under their controlled conditions and paper wastes such as Kraft, cardboard, newspaper and tissue were not recommended as inputs for thermal composting.

Vermicomposting of sludges and paper wastes has been done successfully on an industrial scale in New Zealand (Quintern *et al.*, 2013). In their research, Quintern *et al.* (2013) showed that dairy processing DAF sludge and municipal biosolids can be successfully vermicomposted with pulp and paper mill solids. While these sludges and

paper wastes are different to chicken processing DAF sludge and cardboard, they are similar. The sludges are nutrient-rich with high moisture contents and though they are structurally different, the paper wastes and pulp and paper mill solids are carbon rich.

Vermicomposting (worm farming) is the process of earthworms decomposing organic matter through ingestion and excretion, forming vermicompost where some compost material, uneaten by worms remains, or vermicast where ≥90% of the original material has been ingested and excreted as casts <1.18 mm diameter (Standards New Zealand, 2005). It is primarily carried out by epigeic earthworms such as the tiger worm (*Eisenia fetida* Savigny) (Edwards & Neuhauser, 1988; Domínguez, 2004). As well as producing vermicompost/vermicast, earthworm biomass is another end product of the process, and this has application potential as a protein-rich feed for aquaculture and poultry. Vermicomposting is less studied than composting (Chaudhary *et al.*, 2004) and vermicomposting is still often misunderstood as a niche technology. However, there are model systems capable of processing >200,000 t/yr of organic materials (Quintern, 2022).

Vermiculture focuses on the production of earthworm biomass/cocoons, unlike vermicomposting where the focus is on feedstock throughput and vermicast production (Domínguez, 2004; Dada, 2024).

2.5.1 Earthworms: *Eisenia fetida*

Earthworms are terrestrial invertebrates that fit into three groups based on their feeding and burrowing habits: epigeic (living above the soil), endogeic (living in the topsoil, but foraging on the surface) and anecic (living deep underground) (Bouché, 1977). This thesis researches *Eisenia fetida* Savigny. *E. fetida* is an epigeic compost worm commonly known as the tiger worm, one of the most popular composting worms used commercially. It is also favoured for its prolific and ubiquitous nature as well as its resilience to changes in conditions and handling during harvesting. These features also make it a widely studied organism (Edwards, 1988). Their life expectancy is up to five years (Domínguez & Edwards, 2004).

2.5.1.1 *E. fetida* digestive tract

Earthworm bodies are segmented and lined with setae (fine bristly hairs) used for grip. They are tube-shaped with a mouth at the anterior end and an anus at the posterior end (Darwin, 1881; Julka, 2015). Food particles are grasped by the prehensile mouth (the prostomium, a sensory organ) and swallowed whole. Earthworms have no teeth so there is no biting or chewing action. The food bolus is then taken into the pharynx, then the oesophagus. As the bolus passes through the oesophagus, it is coated with calcium

carbonate ($CaCO_3$) from calciferous glands. The bolus then passes into a crop for storage before it is passed into the gizzard to be mechanically ground with grit. The last stage is passage through the intestine which has a large surface area for absorption before excretion as castings (Darwin, 1881). After the grinding and homogenisation of food in the upper digestive tract, other processes occur in the intestine. High microbial activity occurs in the intestine, resulting in the degradation of organic matter, releasing sugars, modification of microbial populations and the excretion of mucus, urea and ammonia. Post-excretion of vermicast, mesophilic (temperate) microbes continue to decompose organic matter and mineralise nutrients in the vermicast, providing environmental conditions such as moisture are maintained. Earthworms have a direct influence on microbial populations in feedstocks, vermicast and soils (Satchell, 1967).

As well as organic matter, *E. fetida* consume microorganisms as a source of food (Lavelle, 1988). However, Aira *et al.* (2006) reported that higher microbial activity and earthworm activity together means that earthworms are not feeding on microbes and instead are obtaining food from labile organic C and N pools.

2.5.1.2 *E. fetida* lifecycle

Earthworms are hermaphrodites, having both male and female reproductive organs. Earthworm sexual maturity is indicated by the presence of the clitellum – a band or saddle around the body of the earthworm near the head. After mating, clitellum cells secrete a mucous that forms a cocoon (Julka, 2015).

A study by Hartenstein *et al.* (1979) demonstrated that *E. fetida* populations achieved sexual maturity at the same time in feedstocks of activated sludge vs horse manure. This was despite the *E. fetida* growing 2.5 times faster in the activated sludge than those in the horse manure. Within 4-6 weeks, half the populations of *E. fetida* had reached sexual maturity (were clitellate). Worms in lower density populations reached sexual maturity earlier than those in more dense populations. This study also demonstrated that larger worms produced heavier cocoons and heavier cocoons produced more hatchlings. Although cocoons were removed weekly as they were produced, peak cocoon production (approximately 2-5.5 cocoons/worm/week) in horse manure occurred at 9-11 weeks, independent of population density. However, cocoon production appeared to decrease with increasing populations. Cocoon production declined with worm age after the 9-11 week peak. It is understood that continuous rather than batch feeding was employed, indicating the reduction in cocoon production following the peak was due to age, rather than resource availability. The authors also report “considerable mortality” in

the last 4 months (~17 weeks) of their 27-week study. They suggest the weekly/bi-weekly disturbance may have had an adverse effect, or the castings themselves building up in the feedstock may have been toxic, though no evidence of a toxic effect of vermicast accumulation was able to be found in literature. Darwin (1881) also concluded that vermicast is eaten multiple times by earthworms, so it is unlikely to have toxic effects.

Venter and Reinecke (1988) studied the lifecycle of ten *E. fetida* in cattle manure at 25°C and a moisture content of 75% over a period of 600 days. The hatchlings their study began with started to achieve sexual maturity (presence of a clitellum) after 60 days. This is similar to Edwards (1988) who reported 53-76 days to maturity. In Venter and Reinecke (1988), cocoons took four days to form after mating, and subsequent cocoon production started 70 days after hatching, continuing for the duration of the experiment. Cocoon production varied between 10 and 70 cocoons/10 adult earthworms/10 day period, but never stopped over the 600-day experiment. The mean cocoon production rate was calculated to be 0.35 cocoons/earthworm/day. *E. fetida* can produce more than one hatchling per cocoon. In this experiment under optimal conditions, the number of hatchlings per cocoon varied from 1-9 with a mean of 2.7 hatchlings/cocoon, though they were more likely to produce cocoons with one hatchling. The mean incubation period of the cocoons was 23 days, though the data show that this was variable, with a large proportion hatching between 15 and 28 days. Some cocoons took up to 44 days to hatch. Edwards (1988) reported 32-73 days. Interestingly, Venter and Reinecke (1988) reported the 10 adult earthworms continued to increase in biomass over the duration of the experiment. The largest increase in biomass came after the 60-day period when fresh food was added to the system for the first time. However, as the cattle manure feedstock was not identical at each addition, there were some periods where the addition led to a decrease in biomass. It should also be noted that the stocking rate was low (10 earthworms in 320 g cattle manure). Venter and Reinecke (1988) showed that *E. fetida* have a short lifecycle – they reach maturity quickly – and also have a highly reproductive adult life. Though the 10 worms they used for the 600-day trial were not provided with optimal conditions in their first 60 days, the authors have inferred that sexual maturity could be attained within 40-60 days. The 40-day value is likely to have come from additional testing on the 1,725 total cocoons produced, of which 73% hatched, though this is not specified.

Edwards (1988) and Venter and Reinecke (1988) compared their results to data from other compost worm species (*Dendrobaena veneta*, *Eudrilus eugeniae*, *Pheretimahawayana* and *Perionyx excavates*) and concluded that *E. fetida* had the highest

reproductive rate, making them ideal for vermicomposting organic wastes, with the potential to be sources of protein. This is supported by other research e.g. vermicomposting is an appropriate method for the disposal of organic resources (Chaudhary *et al.*, 2004) and *E. fetida* are a suitable source of feed for poultry (Gunya & Masika, 2022). Edwards (1985) recommend that feedstocks are inoculated with young worms and cocoons rather than mature adults if protein/biomass production is desired as this will maximise biomass production (vermiculture). However, for vermicomposting, mature worms are favoured as they can process larger quantities of feedstock at a faster rate.

2.5.1.3 Environmental factors affecting *E. fetida*

Ideal conditions for *E. fetida* to thrive are sufficient oxygen, NH_4^+ content <0.05 mg/g, salt content <0.5%, feedstock temperature 15-20 °C, moisture content 80-90% and pH 5-9, though a pH of 5 is preferred (Edwards, 1985). Later research has updated the optimal temperature conditions for *E. fetida* which are reported to be 25°C, with a tolerance between 0-35°C (Edwards, 1985; Edwards & Neuhauser, 1988). Other factors such as microbial activity, C content and electrical conductivity also affect *E. fetida* activity. Depending on the species and the niche occupied, earthworms require varying amounts of organic matter.

Seven studies reporting a total of 29 different feedstocks were investigated to identify the key parameters involved in determining whether *Eisenia* species (including *fetida*, *andrei* and *eugeniae*) favoured biomass production and subsequently feedstock throughput or reproduction. The data are presented in Table 2-1 and were studied to find a link between C:N and preference for biomass gain or reproduction, however, there was no clear trend. Of the five *E. fetida* trials, one did not report biomass production, however, three studies reported greater biomass production at lower C:N.

The study by Ndegwa and Thompson (2000) reported feedstocks with lower C:N (10 and 15 compared to 20 and 25) resulted in higher biomass production, but this was not significant. Gunadi and Edwards (2003) showed more rapid and greater biomass accumulation with lower C:N (pig waste C:N = 13.2 & 16.9) feedstocks, but greater cocoon production with higher C:N (cattle waste C:N = 32.3 and 36.4). However, the lowest reproductive rate and one of the highest growth rates was reported in the 16.9 C:N sow pig solids feedstock, which interestingly had a very high NH_4^+ content (1,424.4 mg/kg – well above the <0.05 mg/kg threshold reported by Edwards (1985)). Gunadi *et al.* (2003) investigated the effects of moisture content which was important for

E. fetida population dynamics. The results from different moisture contents were averaged across C:Ns. Lower total average biomass production was observed with higher C:N (41.4 vs 15.3), but higher average hatchling and cocoon numbers were observed over the 30 week trial. Lower mortality rates and less variation in these were noted in the lower C:N treatment. Aira *et al.* (2006) showed a significant increase in hatchling numbers for their higher C:N treatment (C:N = 19 vs 11). Gupta *et al.* (2007) showed that higher C:Ns produced significantly more biomass, cocoons and hatchlings (C:N range = 36.0-60.6). Biruntha *et al.* (2020) showed that *E. eugeniae* produced fewer cocoons at higher C:Ns (C:N range 23.9- 69.8). Dume *et al.* (2023) reported that *E. andrei* produced more cocoons and had greater biomass accumulation at lower (very low at 6) than higher (38) C:N. Biomass production and reproduction appear to depend on factors other than C:N alone. Tiunov and Scheu (2004) reported that labile C rather than total C was shown to be an important dietary component for the endogeic earthworm *Octolasion tyrtaeum* (Tiunov & Scheu, 2004). The quality of the C input therefore influences growth and reproduction of earthworms. The variation in chemical parameters of the feedstocks in also indicate that feedstock suitability cannot necessarily be determined at face value. Fernández-Gómez *et al.* (2010) reported the initial inoculation of feedstocks containing heterogenous-plant or tomato-plant wastes failed within 24 hours and attributed this to the high EC content of these wastes (17 ± 0.10 and 12.0 ± 0.01 dS/m, respectively). However, compared to the other wastes trialed in their study, C:N appeared low for both feedstocks (7 ± 0.2 and 9 ± 0.1 respectively) and this may have contributed to mortality (see Section 3.4.2.2 regarding sour crop). In Gunadi and Edwards (2003), young pig solids with a C:N of 9.3 ± 0.4 and EC of 8.2 ± 0.7 dS/m were used as a feedstock for *E. fetida*. As well as a low C:N and high EC, this feedstock had a high NO_3^- content (9,803.2 ± 605.9 mg/kg). However, NH_4^+ content of young pig solids (44.0 ± 4.5 mg/kg) did not appear to be a contributing factor to earthworm mortality as there were other successful feedstocks with higher NH_4^+ contents e.g. sow pig solids (1,424.9 ± 55.2 mg/kg). The sow pig solids feedstock also incidentally had one of the highest growth rates in the first three months (7.8 ± 0.5 mg/day) and the lowest mortality rate in the study after 23 weeks (22%). It is not clear from their data, but EC appeared to have more of an effect than NH_4^+. Possibly, by the time the experiment started, much of the NH_4^+ had been nitrified to NO_3^-, though the authors do not report lag times between collection of this feedstock, sampling, testing and trial initiation. The results of the studies in Table 2-1 demonstrate that earthworm tolerance and suitablity of feedstocks for vermicomposting depend on multiple factors.

2.5.2 Benefits of vermicomposting

2.5.2.1 Vermicast and vermicomposting

Vermicast quality depends on the feedstock inputs. For example, Shrimal and Kwairakpam (2010) showed that initial feedstock C:N dictates the quality of the vermicast and biomass production. Gupta *et al.* (2007), Sharma and Garg (2018), Blesa Marco *et al.* (2023) and Dume *et al.* (2023) showed electrical conductivity (EC) increased during vermicomposting. Their results also show that nutrients tend to concentrate in the vermicast, as volume decreases, though this means heavy metals and sodium also increase. These nutrients are stabilised through the vermicomposting process or they can be managed through precomposting or leaching, reducing the potential for toxic effects of unstabilised mineral nutrients such as NH_4^+ (Domínguez & Edwards, 2004). A study by Ndegwa and Thompson (2000) reported that N content decreased. This is likely due to earthworm uptake. Ratios of C/N are widely reported to decrease during vermicomposting. As well as reducing the volume of the original feedstock (Chaudhary *et al.*, 2004), vermicomposting has been shown to increase the water holding capacity of feedstocks derived from sugar cane press mud (Munnoli & Bhosle, 2011).

While they provide essential services to decomposition and nutrient cycling, earthworms cannot degrade recalcitrant carbon (C; highly resistant to microbial decomposition). Fungi (such as white rot) are needed to break down recalcitrant forms such as lignin. Lignin is the polymer preventing microbial access to cellulose and hemicellulose – biodegradable carbohydrates (Mboowa, 2024). Biruntha *et al.* (2020) demonstrated that *E. eugeniae* reduced both cellulose and lignin contents of different feedstocks (mixtures of cow dung at 1:1 with seaweed, vegetable market waste and coir trash) compared to composting alone over a 50-day period. This resulted in a lower cellulose/lignin ratio in final products, indicating stabilised organic matter.

A review Swati and Hait (2018) stated that variability in pathogen reduction can be attributed to earthworm stocking density and feeding behaviour. While the actual mechanisms of pathogen destruction during vermicomposting have not been confirmed, vermicomposting has been established as an effective method for stabilisation of pathogens in biosolids (Eastman, 1999; Eastman *et al.*, 2001; Edwards & Subler, 2010; Soobhany *et al.*, 2017).

Table 2-1: *Eisenia* species biomass accumulation and reproduction data from seven studies on 29 feedstocks of varying C:N. Other feedstock data are also provided. EC = electrical conductivity. Where trends, but no values were provided, ↑ indicates an increase, ↓ a decrease. Authors did not specify whether NH_4^+ and NO_3^- results were based on dry or fresh matter. *Italicised* values have been estimated from graphs as raw data were not provided. Letters a-d indicate significant differences were detected by the authors and are only relevant within the study.

Parameter	Species	Feedstock	C:N	pH	EC dS/m	NH4 mg/kg	NO3 mg/kg	Mortality	Biomass conversion mg/g feedstock	Biomass production mg/day	Hatchlings	Cocoons	Trial length weeks
Ndegwa and Thompson (2000)	*E. fetida*	Biosolids + paper mulch	10	7.46						↑a			5
			15	7.51						↑a			
			20	7.53						↓a			
			25	7.55						↓a			
Gunadi and Edwards (2003)	*E. fetida*	Young pig solids	9.3	6.2	8.2	44	9,803.2	Toxic					23
		Vegetable wastes	13.1	5.7	12.9	1,878.1	112.6	Toxic					
		Growing-finish pig solids	13.2	6.8	4.5	227.3	558.2	75%		8.5 ± 0.8 (1st 3 months)a		4.4 ± 0.1/worm c	
		Fruit wastes	15.9	4.1	4.5	3.5	ND	100%		0.1 (3rd week)			
		Fresh cattle solids	16.1	7.2	3.2	150.1	11.4	100%		1.5 (2nd week)			
		Sow pig solids	16.9	8.8	3.2	1,424.4	ND	22%		7.8 ± 0.5 (1st 3 months)a		1.8 ± 0.1/worm d	
		Pre-composted cattle solids	32.3	8.5	3.4	21.2	ND	28%		4.7 ± 0.7 (1st 3 months)b		7.6 ± 0.1/worm b	
		Separated cattle solids	36.4	8.9	3.2	5.3	4.2	34%		4.6 ± 0.6 (1st 3 months)b		9.5 ± 0.1/worm a	

Parameter	Species	Feedstock	C:N	pH	EC dS/m	NH4 mg/kg	NO3 mg/kg	Mortality	Biomass conversion mg/g feedstock	Biomass production mg/day	Hatchlings	Cocoons	Trial length weeks
Gunadi et al. (2003)	*E. fetida*	Cattle manure	15.3			657.9	76.7	52%	2.3	8.7 (/worm)a	30	15	30
		Pig manure	41.4			35.1	16.6	7%	2.2	5.9 (/worm)b	323	216	
Aira et al. (2006)	*E. fetida*	Pig slurry	11								33 ± 30b	782 ± 105	6
		Pig slurry	19								472 ± 201a	750 ± 198	
Gupta et al. (2007)	*E. fetida*	Water hyacinth + cow dung	36.0	8.1				0%	3.1 ± 0.2a	20.8 ± 0.45a	0 ± 0.0a	0 ± 0.0a	21
			39.5	8.0				0%	24.7 ± 4.3b	168.2 ± 16.8b	189 ± 34.6b	135 ± 32.8ab	
			47.2	8.2				0%	32.4 ± 7.0b	220.3 ± 27.4b	402 ± 27.4c	167 ± 29.6b	
			56.7	8.1				0%	63.1 ± 4.6c	428.0 ± 17.9c	691 ± 38.1d	266 ± 23.4bc	
			60.6	8.2				0%	91.0 ± 7.0d	619.1 ± 17.9 (all worms)d	859 ± 28.7e	348 ± 36.6c	
Biruntha et al. (2020)	*E. eugeniae*	Seaweed + cow dung	23.9	7.49	1.49					*7.8*		*0.26/worm* a	7
		Sugarcane trash + cow dung	41.8	7.41	2.09					*7*		*0.23/worm* b	
		Coir pith + cow dung	48.2	7.48	1.65					*5*		*0.20/worm* c	
		Vegetable market waste + cow dung	69.8	7.57	1.76					*4.5*		*0.17/worm* d	
Dume et al. (2023)	*E. andrei*	Sewage sludge	6	6.9	*0.65*					↑a		↑a	17
			18	7.3	*0.65*					↑b		↑a	
			28	*7.7*	*0.65*					↑b		↑b	
			38	*8.0*	*0.65*					↑b		↑c	

Eastman *et al.* (2001) showed that *E. fetida* added at 1:1 *E. fetida*:municipal biosolids had a significant effect in rapidly reducing human pathogens (within a few days to a week) compared to a non-vermicomposting control. They reported that vermicomposting reduced faecal coliforms and *Salmonella* by 100%. While the non-vermicomposting control also reduced human pathogens, reductions took significantly longer. The control also did not achieve the same level of sanitation for *Salmonella* (99.99%). Vermicomposting achieved a 99.99% reduction in enteric viruses, while the control achieved 98.46%. Enteric virus reductions were significantly faster in the vermicomposting treatment. Vermicomposting achieved a 98.87% reduction in helminth ova, while the control achieved 74.24%. However, not all studies show pathogen levels are well managed during vermicomposting e.g. (Cao *et al.*, 2016).

These characteristics indicate that the process of vermicomposting can add value to organic wastes through bioconversion.

2.5.2.2 Earthworm biomass and vermiculture

Shanmugam *et al.* (2025) reported that valorisation of organic wastes can lead industries to work within circular economies. Their experiments showed that chicken DAF sludge could be converted to black soldier fly larvae (BSFL) biomass and frass, especially when mixed with food waste. They conclude by suggesting that slaughterhouse solid wastes could be upcycled into poultry feed, however, this would not likely be possible due to the risk of pathogen transmission through the use of poultry waste products as an input. Earthworms also have a high crude protein content, making them an ideal alternative supplemental feed for poultry (Gunya & Masika, 2022). However, the issue here is about the link between using poultry wastes to produce feed for poultry, not the method of valorisation. There is a risk of disease perpetuity in producing food for an organism from its own wastes. However, other options for invertebrate protein from poultry processing exist such as protein rich meal for aquaculture. In addition, earthworms have also been suggested as an alternative invertebrate protein for human consumption (Kostecka *et al.*, 2022).

2.5.3 Benefits of earthworms and vermicast application

Vermicast application has been widely studied internationally. Earthworms provide benefits for plants, increasing production in a variety of crops (van Groenigen *et al.*, 2014). According to van Groenigen *et al.* (2014)'s review, the effects of earthworms on crop production "will help to bridge the yield gap with conventional agriculture". Earthworm presence can increase soil water holding capacity, especially when more

labile, rather than recalcitrant C is available (Tiunov & Scheu, 2004). These earthworms have also been shown to increase mineralisation of nutrients, making them more plant available. It is clear that as well as their role in decomposition, earthworms provide significant ecosystem services, turning over soil, mixing organic matter and influencing soil structure (Darwin, 1881). Their presence is beneficial to plants. However, just the application of vermicast, without the presence of earthworms, has benefits for plant production. A meta-analysis by Blouin *et al.* (2019) found significant improvement in commercial yield (26%), shoot (+78%), root (+27%) and total plant (13%) biomass when vermicast was applied. The study investigated subgroups such as dose of vermicast, combination with mineral fertiliser, plant functional groups, material vermicomposted and growing environment. In almost all cases, vermicast had a positive effect on plant production.

2.5.4 Industrial scale vermicomposting in New Zealand

Noke Ltd. trading as 'MyNoke™' is New Zealand's largest vermicomposting operation, having processed over 1.3 million tonnes of organic resources in New Zealand since 2008 (Quintern, 2022). Organic resources converted into vermicast include, but are not limited to, pulp and paper mill solids and odorous/pathogenic sludges such as waste activated sludge (WAS), dissolved air flotation (DAF) from dairy factories, and municipal biosolids (Quintern *et al.*, 2013). The system employed by MyNoke is based on the Windrow Vermicomposting System (Edwards & Neuhauser, 1988), but with improvements that reduce labour requirements, land footprint, risk of nutrient losses e.g. via leaching and an improved harvesting method that does not require earthworm separation from the vermicast at maturity (Quintern *et al.*, 2016). Images of the MyNoke industrial scale vermicomposting process are displayed in Figure 2-2a-e.

After vermicomposting, which takes approximately 12 months, vermicast is harvested, screened and exported from the vermicomposting site. It can be applied on neighbouring paddocks or exported to other agricultural/horticultural sites. Application can be made with muck spreaders, or screened product can be applied using fertiliser spreaders. After harvest, some vermicast and earthworms remain on site. As well as rotational management to spread the benefits and nutrient loading on the land (Quintern, 2022), a catch crop can be sown after vermicomposting to minimise the risk of nutrient loss from soils and maximise the opportunity to gain benefits from the vermicast (Quintern *et al.*, 2016; Quintern & Morley, 2017).

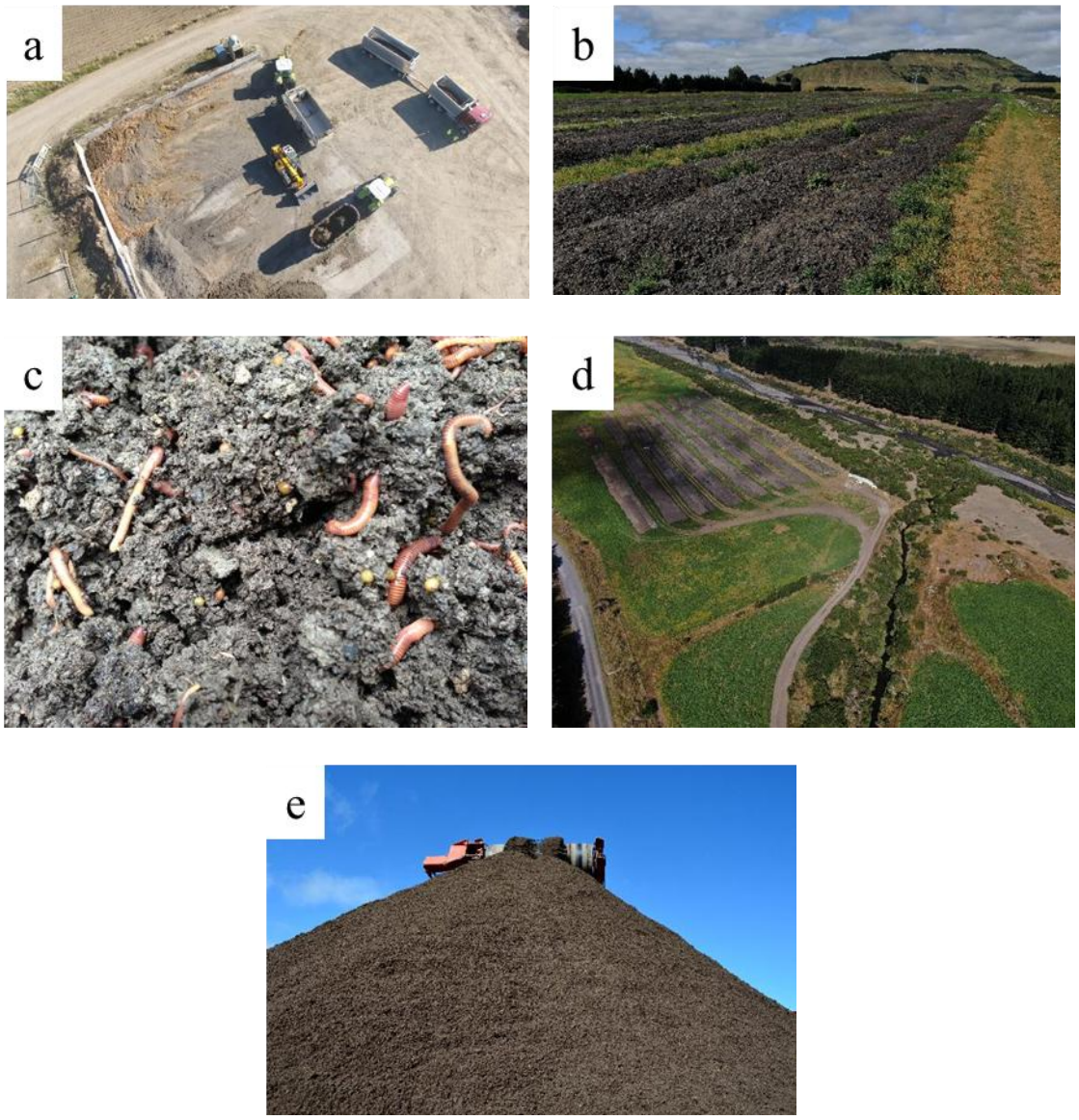


Figure 2-2a-e: Images: MyNoke

a: Aerial image of reception and processing site where organic inputs are delivered and mixed before being carted to the vermicomposting site.

b: Vermicomposting windrows (feedstock) at a MyNoke vermicomposting site.

c: *Eisenia fetida* (tiger worms) and capsules in feedstock. Earthworm capsules (containing eggs) indicate the feedstock is suitable for breeding.

d: Aerial image of MyNoke vermicomposting site on farmland (lucerne crop). The vermicomposting process has been integrated into the existing farm management. e: Screened vermicast stockpile. Vermicast screened to 20 mm can be applied to land with standard fertiliser spreaders.

Vermicomposting of organic resources on existing farmland can provide multiple benefits for landowners. MyNoke's model system integrates organic resource management into existing farmland e.g. pasture or crop paddocks, providing an outlet for organic waste producers and a source of vermicast and earthworms for the landowner (Quintern, 2022). Figure 2-3 depicts this model.

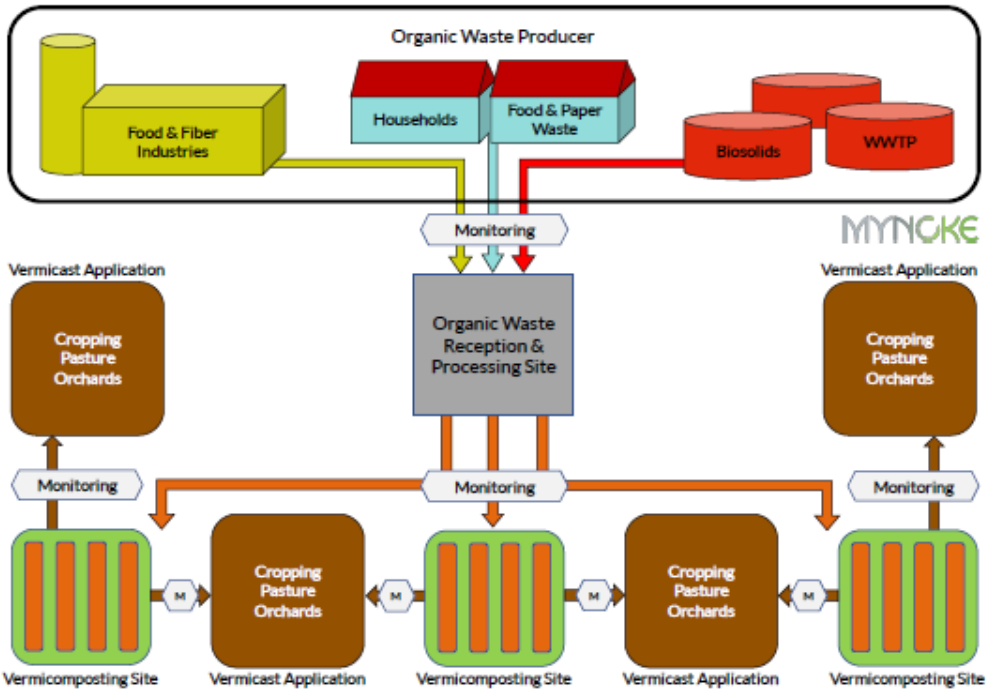


Figure 2-3: MyNoke™ vermicomposting model showing integration of vermicomposting process into existing farmland (multiple Vermicomposting Sites) with a centralised Organic Waste (resource) Reception and Processing Site. Reprinted with permission of Quintern (2022). See Figure 2-2a-e.

2.6 Circular economy in New Zealand food production

To maintain production and minimise damage caused by conventional agriculture to the environment, alternative methods for fertilisation and restoring and maintaining soil quality are needed (Edmeades, 2003; Cordell *et al.*, 2009). An integrated food production system designed to avoid waste and operate within a circular economy is proposed as a solution to these local and global challenges.

Conventional farm systems are not designed to be circular. They tend to be linear in the sense that waste products are produced throughout a product's life cycle and are eventually wasted through disposal to landfills. The concept of circular farm systems involves utilising materials and products at their highest possible level. Principles proposed by de Boer and van Ittersum (2018) include (i) using plant biomass to produce food directly for humans, rather than feed for animals, (ii) recycling by-products back into food production systems, and (iii) using animals for what they are good at.

In this literature review, opportunities have been identified to alter food production systems to better align with circular economy principles. In this thesis, chicken processing DAF sludge and (ideally non-recyclable) paper waste are proposed as a mixed feedstock for *E. fetida*. As paper waste nutrients and carbon are unavailable as a food

source for humans, it seems little can be done to upcycle this waste product into food. Chicken processing DAF sludge is not suitable as a food source for humans. Through disposal to land, its nutrients do eventually end up in food for humans via animal products. However, reuse of these nutrients could be improved. By mixing DAF sludge with paper waste and feeding it to *E. fetida*, the nutrients in both products can be converted into vermicast. This vermicast could then be used to grow food crops such as onions, potatoes and maize. The by-products are recycled and value is added with nutrients being recycled back into food production and using *E. fetida* to add value to these through vermicomposting.

2.7 Novelty of research topic

At the time of writing this literature review, there was no published research available on vermicomposting chicken processing DAF sludge and non-recyclable paper waste. This thesis investigates the potential for these two organic resources to be vermicomposted into a beneficial vermicast to improve food production, closing nutrient loops and shifting nutrient use in conventional agriculture from linear to circular.

In addition, the research carried out on vermicast, tends to be done at small scale and there are few studies researching repeated vermicast application in a rotational cropping system. Here, the application of industrially produced vermicast to multiple crops on a commercial market garden farm is investigated. Finally, this thesis also investigates a few nuances of vermicast application, including the potential for vermicast to be used as a supplement for imported, non-renewable rock phosphate fertiliser derivatives.

This thesis is relevant to the Aotearoa Horticulture Action Plan, as it investigates the potential for alternative nutrient sources which could reduce the sector's reliance on imported fertilisers such as phosphorus, offsetting production costs and increasing farmgate value.

Chapter 3
Vermicomposting trials: Dissolved Air Flotation sludge from poultry processing

This section describes the lab-scale (≤10 kg feedstock) vermicomposting trials conducted to determine the appropriate ratio of fibre (cardboard) and dissolved air flotation (DAF) sludge required for conversion of the feedstock into vermicast. A pilot trial to determine suitability of DAF and cardboard as a feedstock for vermicomposting was conducted first. The main vermicomposting trial was designed to produce a vermicast that could be tested against the New Zealand Standard for composts, soil conditioners and mulches NZS 4454:2005. Due to similarities in the trial designs and aims, this chapter is structured so that the methodology, results and discussions of the pilot and main trials are reported in the same major sections (Methods and Results), but the pilot trial is always reported on first as a subsection.

3.1 Background and trial purpose

Chicken processing DAF sludge is a nutrient-rich and odorous by-product of chicken processing. In general, this organic waste product is land applied without stabilisation both overseas (Shanmugam *et al.*, 2025) and in New Zealand (Artika Devi, personal communication, July 15, 2025). Vermicomposting may be a suitable option for stabilisation and valorisation of nutrients as well as managing the odours associated with the sludge. A pilot trial was conducted to assess the suitability of DAF as a vermicomposting input.

This part of the research project was designed to determine whether DAF would be a suitable material for vermicomposting with an end use as a soil conditioner. A vermicast or vermicompost derived from DAF would need to pass specific criteria outlined in the NZS 4454:2005 New Zealand Standard Compost, Soil Conditioners and Mulches Standards New Zealand (2005) to be considered successful (Table 3-1). While these standards are voluntary, they provide useful guidelines for beneficial vermicast products. However, Regional Councils usually require large-scale vermicomposting operations to obtain Resource Consent. Mandatory requirements often include vermicast or vermicomposting processes to meet standards such as NZS 4454:2005 or the biosolids guidelines (Ministry for the Environment, 2021b). It was not practical to follow the

informative best practice guidelines for vermiculture systems as the trial was designed only to test the given feedstocks, not to produce vermicast commercially. If a vermicast derived from DAF met the relevant NZS 4454:2005 standards, it would be considered suitable for vermicomposting although large scale tests would be required to confirm its suitability for industrial scale vermicomposting. The following trials are lab-scale trials investigated the potential for DAF to be used as a feedstock for vermicast.

Table 3-1: Tests and thresholds for the New Zealand Standard for composts, soil conditioners and mulches NZS 4454:2005. DM = dry matter.

Appendix	**Test**	**Threshold**
Microbiological tests		
	E. coli	
Chemical tests		
A	pH	5.0-8.5
	EC	No limit, but notes about sensitive plants
	NH_4^+-N + NO_3^--N	>10 mg/L if a contribution to plant growth claimed
	Soluble P	≤5 mg/L if a contribution to plant growth claimed
B	C	Not specified
	N	Not specified
	Organic matter content	≥25% DM
C	P	≤0.1% DM if a contribution to plant growth claimed
	B	
	Ca	<200 mg/kg DM
	Mg	Not specified
	Na	Not specified
		Not specified
-	As	20 mg/kg DM
	Cd	3 mg/kg DM
	Cr	600 mg/kg DM
	Cu	300 mg/kg DM
	Hg	2 mg/kg DM
	Ni	60 mg/kg DM
	Pb	250 mg/kg DM
	Zn	600 mg/kg DM
F	Moisture content	>25 %
-	Organic contaminants	Not tested in this trial
Biological tests		
D	Toxicity test	Root length >20 mm
J	Plant propagules	Nil after 28 days
N	Plant growth index	Not required, but ≥2
-	Biology	No method recommended
Physical tests		
E	Particle size grading	>90% of particles must be <1.18 mm
G	Volume and mass (bulk density)	Not specified
Contamination		
P	Glass, metal and rigid plastic	≤0.4% DM w/w
	Stones and lumps of clay	≤5% DM w/w
	Plastics – light, flexible or film	≤0.04% DM w/w
Q	Large particles	<10% of particles must be >1.18 mm

3.2 Methods

3.2.1 Pilot trial

From mid-October 2024 to late March 2025, a pilot trial was conducted to test the viability of vermicomposting DAF at small scale with the addition of cardboard as a carbon source and bulking agent.

3.2.1.1 Pilot trial input resources

On 27 September, 10 kg of DAF from a North Island chicken processing plant was collected and stored for two weeks at ambient temperatures in a 20 L lidded bucket until the beginning of the trial. The lid was left cracked open to allow gasses building up to escape and prevent flies contaminating the product. The storage site was outdoors, under shelter and out of direct sunlight. Clean (uncontaminated with food, plastics, inks, etc.), single-walled corrugated cardboard from one sheet was cut into 30 x 30 mm pieces. The dry matter content of each input was measured by oven drying for 3 days at 105 °C.

A 20 L bucket with holes punched in the lid for ventilation was filled with *Eisenia fetida* in bedding material (primary and secondary pulp and paper mill solids) on the DAF collection day.

The trial began on 9 October 2024 with the mixing of the feedstocks. A sample of DAF sludge was taken with sterile equipment for enterococci testing, immediately prior to mixing the feedstocks. This sample was refrigerated and submitted for analysis the next day. Enterococci testing was chosen over other tests such as *Escherichia coli* or faecal coliforms as it was an affordable faecal microbial hygiene indicator. The method used by the laboratory was membrane filtration, plating on mEI agar, incubation at 42°C for 24 hours prior to counting. The referenced method is APHA 9230 C (modified) Online Edition.

3.2.1.2 Pilot trial design

The trial was a two-factor full factorial design. Factor A was the feedstock composition. There were four levels: pure DAF, 2:1 Cardboard:DAF, 3:1 Cardboard:DAF, and 4:1 Cardboard:DAF. Factor B was the processing method. There were two levels: composting (no worms), and vermicomposting (inoculation with *E. fetida*). In total there were eight treatments. Each treatment combination was replicated three times, resulting in 24 experimental units.

Each experimental unit was kept in individual, undrained, clear plastic containers, each with a total volume of 1.4 L and a feedstock surface area of 113 cm^2. The lids of the

containers were modified to allow ventilation and prevent worm escape by cutting a (60 x 130 mm) window from the centre and taping nylon mesh with 1 mm diameter holes over the windows. The tare mass of each container and lid was recorded to determine feedstock mass for weekly moisture content maintenance.

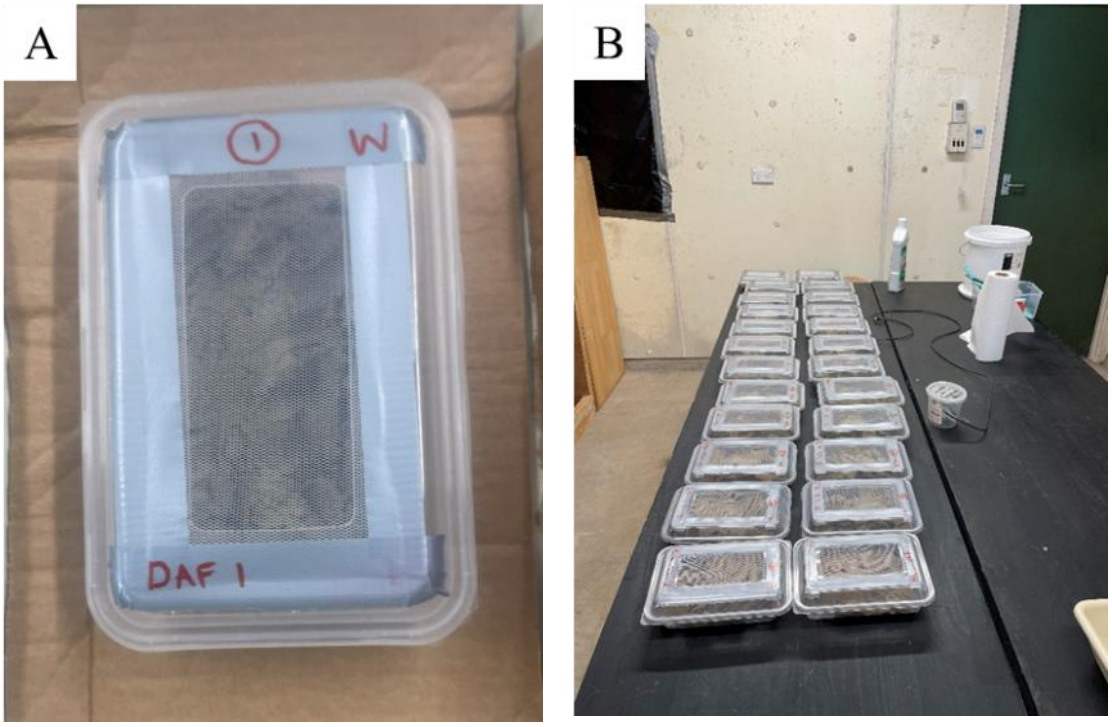


Figure 3-1: A = experimental unit. B = Trial set up (24 units).

3.2.1.3 Pilot trial set up

A total of 50 g dry matter (DM) was added to each container at the initiation of the trial. When water was added to equalise the treatment moisture contents, this was a total of 205 g fresh matter (FM) for treatments containing both cardboard and DAF sludge and 297.2 g FM for those containing pure DAF. The difference in total FM was due to the lower moisture content and water holding ability of the cardboard than the DAF sludge. For each experimental unit, the appropriate amount of cardboard, DAF and water was weighed into a large container according to the ratios in Table 3-2, hand mixed with a silicone spatula and placed into the appropriate pre-labelled container. Between each experimental unit, all equipment was wiped clean with paper towels and distilled water to avoid cross contamination that could alter C:N ratios.

To avoid moisture content influencing the processing of the treatments, distilled water was added to all treatments containing cardboard to achieve an overall feedstock moisture content of 76%. This was based off the maximum quantity of water the 4:1 Cardboard:DAF treatments, i.e. the treatments with the highest cardboard content, and therefore the poorest ability to hold water, could retain.

Samples of cardboard, DAF and the three Cardboard:DAF feedstocks were collected, triple bagged and frozen for later analysis as the odour of the DAF sludge was very strong.

The moisture content was maintained on a weekly basis by weighing the container, subtracting the container and lid mass and topping it back up to the original feedstock mass (excluding worm mass, if relevant) with distilled water using a mister for the first six weeks to maximise the surface area wetted, then a squeeze bottle as water requirements increased. The pure DAF treatments were maintained in the same manner, but at the DAF's original moisture content of 83%.

Worms were voided the day before the trial began. Fifty *E. fetida* worms were left on wet paper towels in a sealed container in the dark. The paper towels were changed once in the 24-hour period. Five clitellated worms (sexually mature, averaging 1.9 g total) randomly selected from the 50 voided worms were added to each container immediately after mixing (inoculation). These worms did not survive and were removed from the experiment the following week. The inoculation was reattempted successfully in early December after a seven-week pre-composting period, and the number of adult worms topped up to five every four weeks, as needed, following this. At five worms per treatment, the stocking rate maintained was 0.17 kg worms/m^2 or 0.38 g worms/g feedstock FM.

Each month, the number of mature, juvenile and dead worms and total cocoons were counted in each vermicomposting container. These were removed as they were counted and then returned to the feedstock. The mass of mature worms was recorded. Dead worms were removed and weighed as they were discovered, with minimal disturbance of the feedstock, if practical.

The experiment was kept indoors in a dark, unheated room. Ambient temperature was monitored with a data logger.

Presence of microbial colonies on the treatments was recorded as a description weekly. The texture, presence of ponding and other observations were also recorded. Photographs of one replicate from each treatment were taken prior to watering. After watering, the containers were placed on the bench in a random order.

At the end of the trial, DM of the remaining feedstock (after removing worms and capsules) was measured after oven drying for 5 days at 105 °C.

Table 3-2: Treatment dry masses (DM), fresh masses (FM), water volume added, C:N and final moisture contents for the pilot vermicomposting trial.

Ratio (DM basis)		Dry Mass			Fresh mass			Water				Feedstock		Moisture content
Cardboard :	DAF	Cardboard	DAF	Total	Cardboard	DAF	Total	Cardboard	DAF	Added	Total	Total	C:N	
		kg DM/tub			kg FM/tub			kg H_2O/tub				kg/tub		
0	1		50.0	50.0		297.2	297.2		247.2	0	247.2	297.2	8.8	83%
2	1	33.3	16.7	50.0	36.3	99.1	135.4	3.0	82.4	69.6	155.0	205.0	24.5	76%
3	1	37.5	12.5	50.0	40.9	74.3	115.2	3.4	61.8	89.8	155.0	205.0	31.9	76%
4	1	40.0	10.0	50.0	43.6	59.4	103.0	3.6	49.4	102.0	155.0	205.0	39.1	76%

Table 3-3: Treatment dry masses (DM), fresh masses (FM), water volume added, C:N and final moisture contents for the main vermicomposting trial.

Tubs	Ratio (DM basis)		Dry Mass			Fresh mass			Water				Feedstock		Moisture content
	Cardboard	DAF	Cardboard	DAF	Total	Cardboard	DAF	Total	Cardboard	DAF	Added	Total	Total	C:N	
			kg DM/tub			kg FM/tub			kg H_2O/tub				kg/tub		
1A, 4B	2	1	1.667	0.833	2.500	1.823	4.630	6.453	0.157	3.796	2.984	6.938	9.438	23.8	74%
2A, 5B	3	1	1.875	0.625	2.500	2.051	3.472	5.524	0.176	2.847	3.914	6.938	9.438	29.2	74%
3A, 6B	4	1	2.000	0.500	2.500	2.188	2.778	4.966	0.188	2.278	4.472	6.938	9.438	32.5	74%

Table 3-4: Cardboard and Dissolved Air Flotation (DAF) sludge C:N results and dry matter (DM) results for pilot and main vermicomposting trials

	C %DM	N %DM	C:N	DM
Cardboard (pilot trial)	46.6	0.1	429.2	91.8%
DAF sludge (pilot trial)	49.5	5.6	8.9	16.8%
Cardboard (main trial)	49.2	0.7	71.5	91.4%
DAF sludge (main trial)	58.3	6.7	8.7	18.0%

3.2.1.4 Analyses

Input, feedstock and final product elements were determined using an Agilent 8900 Inductively Coupled Plasma – Mass Spectrometer (ICP-MS; Agilent Technologies, Santa Clara, California, USA) controlled by MassHunter Workstation (version 4.5). Samples were first dried at 50 °C for one week and ground in a ball mill grinder (Retsch Mixer Mill MM 400) at 27.5 Hz for 60 seconds. Approximately 0.2 g of the ground samples were pre-digested overnight in reverse aqua regia (3:1 concentrated HNO_3: HCl) before digestion in a water bath set to 90 °C for 1 hour. Digests were then topped up to 50 mL with Type 1 (ultrapure) water before a 15 mL subsample was filtered through a 0.45 µm filter. The subsamples were diluted 100x by taking 0.1 mL filtered digest, adding 9.7 mL Type 1 water and 0.2 mL HNO_3 to achieve a 2% HNO_3 concentration in the sample prior to analysis for Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, P, Pb, S, Sr, Tl, U, V, Zn.

From the remainder of the subsamples ground for ICP-MS analysis, a minimum of 2 g was submitted for C:N analysis. Total carbon and nitrogen were analysed using an Elementar Vario-Max CN Elemental Analyser (Elementar GmbH, Hanau, Germany). The sample was combusted at 900°C in an oxygen atmosphere. The combustion process converts any elemental carbon and nitrogen into CO_2, N_2 and NO_x. NO_x are subsequently reduced to N_2. These gases were then passed through a thermal conductivity cell to determine CO_2 and N_2. Results were reported in elemental % as received. As DM was not tested directly on the C:N samples due to small sample sizes, a range of similarly treated samples were tested for DM and found to be 90% DM on average. This DM content was used to calculate C and N contents as %DM.

Although worms were not voided or rinsed at the final weighing, one-way analysis of variance (ANOVA) were conducted on the total and average final biomass of worms in the Cardboard:DAF treatments. Assumptions were assessed using Shapiro-Wilk (normality), Levene's test (homogeneity of variance), and a non-parametric Kruskal-Wallis test. The pure DAF treatment was excluded from analysis, as no worms survived and the absence of variance violated ANOVA assumptions.

No statistical analysis was performed on worm counts due to the low stocking rate (five worms per replicate).

An ANOVA followed by a Tukey Honest Significant Difference (HSD) test was conducted on the dry mass of feedstock remaining at the conclusion of the trial.

3.2.2 Main trial

The aim of the vermicomposting trial was to produce a viable vermicast from cardboard + DAF mixes. Success would result in a product that met specific criteria outlined in the NZS 4454:2005 New Zealand Standard Compost, Soil Conditioners and Mulches Standards New Zealand (2005). These are hereon referred to as the "Standards".

3.2.2.1 Main trial resources

On 4 March 2025, corrugated cardboard from uncontaminated, but used, SpaceKraft® Liquid IBC packaging with seven-wall construction (~60 mm thick) was shredded in a Soyu SRB Series Swing Arm Single Shaft Shredder shredding machine. The shredded pieces were passed through the shredder twice more to further reduce the size of the pieces. In total, 15 kg fresh matter (FM) was produced, with approximately 46% of the pieces between 16 and 32 mm, determined by sieving (Table 3-5). Twenty-five kilograms fresh matter (FM) DAF was collected from the same North Island chicken processing plant that supplied DAF for the pilot trial The DM content of each input was measured by oven drying overnight at 105 °C. The trial began on 5 March 2025 with the mixing of the feedstocks.

Prior to the initiation of the trial, three 20 L buckets with holes punched in the lid for ventilation were filled with *E. fetida* in bedding material (primary and secondary pulp and paper mill solids) from the Tokoroa vermicomposting site in 2024. *E. fetida* were also raised in two other feedstocks kept in 120 L wheelie bins: chicken litter mixed with cardboard and vermicomposted pulp and paper mill solids, and DAF leftover from the pilot trial mixed with shredded paper waste and vermicomposted pulp and paper mill solids. The worms were left to breed until required for the experiment.

Table 3-5: Sizes of shredded cardboard pieces determined by sieving.

Cardboard sizes	Proportion of cardboard
>63 mm	0%
32-63 mm	19.4%
16-32 mm	45.5%
8-16 mm	25%
<8 mm	10%

3.2.2.2 Main trial design

The trial was a completely randomised design with one factor at three levels. The factor was the feedstock composition. The three levels were: 2:1 Cardboard:DAF, 3:1 Cardboard:DAF, and 4:1 Cardboard:DAF. Each treatment combination was replicated twice, resulting in six experimental units (Table 3-3).

Each experimental unit was kept in individual, undrained, 40 L plastic tubs with a feedstock surface area of 0.126 m^2 (see photos A-C in Figure 3-23). Fungus gnats and flies were known to be attracted to the feedstock, based off the results of the pilot trial. To reduce the chances of colonisation, the handles of the tubs were cut off and fine net curtains were taped to the top of the tubs for the initial nine-week pre composting period (see photo P in Figure 3-23). The curtains allowed ventilation, but the holes were too small for fungus gnats to get through. Yellow sticky traps were also set around the trial for monitoring and to further reduce colonisation opportunities prior to worm inoculation.

As for the pilot trial, the mass of each container (and curtains) was recorded to determine feedstock mass for weekly moisture content maintenance.

3.2.2.3 Main trial set up

A total of 2.5 kg DM (9.438 kg FM per treatment) was added to each tub at the initiation of the trial, according to the ratios in Table 3-3. The feedstocks were hand mixed with a metal scoop and silicone spatula. Between each experimental unit, all equipment was wiped clean with paper towels and 70% ethanol.

To avoid moisture content influencing the processing of the treatments, distilled water was added to all treatments containing cardboard to achieve an overall feedstock moisture content of 74%. This was based off the maximum quantity of water the 4:1 treatments, i.e. the treatments with the highest cardboard content, and therefore the poorest ability to hold water, could retain.

206 g samples of cardboard, DAF and the three Cardboard:DAF feedstocks from one set of replicates were collected and frozen for later analysis.

A pre-composting period ran for nine weeks from 5 March 2025 to 8 May 2025. During this time, the 74% moisture content was maintained on a weekly basis by weighing the tub, subtracting its mass and topping it back up to the original feedstock mass with distilled water using a watering can. The added water was mixed in with the metal scoop and spatula until worms voluntarily moved into the feedstocks. Note that watering method and rates changed throughout the trial. From Week 9 to Week 18 a 2 L pressure sprayer was used and no mixing followed. From Week 18 to Week 27, leachate

was present. A maximum of 10-40 mL distilled water per tub was misted on the surface to prevent a crust forming and to allow the feedstock to dry to the point where no more leachate was present. A layer of woven weed matting was also laid on the feedstock surface to prevent crust formation and to provide the worms protection from direct light. From Week 27 to Week 35, up to 200 mL of distilled water was misted weekly per tub with the same proportion of water (10% of weekly FM loss) applied to each tub.

The experiment was kept indoors in a dark, room until the date of inoculation. After this time, the lights were left on 24/7 to deter worms from leaving their assigned treatments and a heater was used between 5 pm and 9 am to maintain ambient temperature between 15-25 °C. Ambient temperature minimum and maximum were monitored throughout the trial with a digital thermometer.

In Week 9 (7 May 2025), a heater on a thermostat set to maintain the room temperature between 15-25 °C was introduced.

In Week 21, the trial was moved into another room with the same temperature and light conditions, but with an additional ventilation window to the outside.

3.2.2.3.1 Main trial E. fetida *inoculation*

The suitability of the treatments for worm inoculation was assessed by monitoring the survival of test worms added to the vermicomposting treatments. Five *E. fetida* worms were added to each tub in Week 5 (10 April 2025), and again into the 2:1 and 3:1 tubs in Week 7 (23 April 2025).

On 7 May 2025, for each of the six tubs, 250 clitellated and unclitellated worms (~150 g) were harvested from the breeding bins described in Section 3.2.2.1. The total worm count was made up of 100 clitellated worms (62 g) from the pulp and paper mill primary and secondary solids feedstock, 100 clitellated worms (82 g) from the DAF + cardboard feedstock and 50 unclitellated worms (24 g) from the chicken litter + cardboard feedstock. Six plastic 2 L containers with lids were filled with 550 g pulp and paper mill primary and secondary solids as bedding and the six lots of 250 worms were added to these. The containers were stored in the experiment room with the lids cracked open for ventilation and the lights on to deter escape. On 8 May 2025, the bedding material containing the worms for each of the six tubs, was placed into labelled inoculation socks using a large funnel. The inoculation socks were nylon mesh tubes with 3 mm diameter holes measuring 150 x 300 mm and sewn shut at one end. A pad of nylon mesh with 1 mm diameter holes was tucked into the sewn end, to prevent fine bedding material from falling out as the socks were filled. The inoculation socks were

topped up with another 450 g bedding material and weighed, before being laid on the appropriate feedstock in the centre of the tub. This step is referred to as 'inoculation'. However, this is not necessarily the point at which the worms voluntarily moved in. The bedding material in the inoculation sock was there to give the worms an environment they could survive in if the conditions in the feedstock were not suitable.

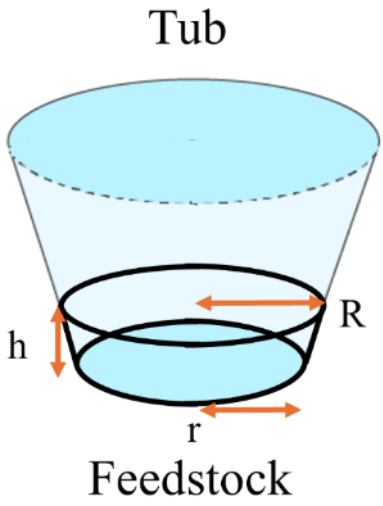
3.2.2.3.2 Main trial weekly monitoring

Each week, the feedstock was weighed and a description of the feedstock texture, presence of microbial colonies and other observations such as worm behaviour and mortalities were recorded. Photographs of the feedstock in each tub were taken prior to watering. Where inoculation socks were present, a photo was also taken of the interface between the inoculation sock and the feedstock surface, as an indication of worms voluntarily moving into the feedstock. Worms were considered to have successfully moved into the feedstock when at least two-thirds of the worms had moved out of the inoculation sock. Stragglers were moved into the tubs by hand.

Weekly measurements were taken as follows: pH from Week 7, electrical conductivity (EC) from Week 8, average feedstock height (to calculate bulk density (BD)), feedstock temperature from Week 9 and ammonia (NH_3) presence from Week 11.

The weekly EC, pH and NH_3 measurements were done on 1:5 W/V extracted samples. After watering the feedstock (and mixing, if applicable), a 10.00 g ± 0.05 g subsample was taken from each feedstock surface and placed in a 100 mL lidded plastic container. Fifty millilitres of distilled water was measured using a measuring cylinder and added to each subsample. The samples were then mixed by pulsing each one five times with an overhead stirrer. The samples were then placed on an end-over-end shaker for 60 minutes at 60 RPM. The pH and EC of the samples were measured immediately using a Eutech pH 700 pH meter, set up for three-point calibration. The pH meter was calibrated just before testing, each week. The EC meter was calibrated monthly using 2 M KCl. Ammonia content was measured using J-QUANT ammonia 6 test strips (range 0-6 mg/L NH_3) after pH and EC had been measured.

Bulk density was calculated using feedstock FM and the volume of feedstock in the tubs. The volume of feedstock was calculated by averaging five measurements of the feedstock height and using this in the formula for volume of a conical cylinder (the shape of the tubs). See Figure 3-2. Bulk density was calculated by dividing feedstock FM by the calculated volume.



$$Feedstock\ volume = \frac{1}{3\pi h(r^2 + rR + R^2)}$$

Figure 3-2: Diagram of dimensions used to calculated feedstock volume in experimental tub (conical cylinder). R = radius at top of feedstock, r = radius at base of tub, h = height of feedstock (n = 5).

3.2.2.3.3 Trial completion

In Week 36, four weeks to the completion of the 40-week trial, all feedstocks were mixed by hand, inverting the material and breaking up large clumps. A subsample of each was taken for DM analysis. No watering occurred after this period.

3.2.2.4 Main trial analyses

As the aim of this trial was to produce vermicast for testing against the Standards there was limited replication (two replicates per treatment). This meant no formal statistical analyses were able to be performed on the treatments.

3.2.2.4.1 Dry matter analysis

Dry matter of the feedstock was measured on 3rd September 2025 (Week 26) and weekly from 12 November 2025 (Week 36) after the mixing event. Dry matter was determined by taking a 10 g representative subsample of the feedstock and drying in an oven at 105 °C.

3.2.2.4.2 Input, feedstock and final product analyses

The same methods used for the pilot trial were used for the main trial. Refer to Section 3.2.1.4 for ICP-MS and C:N analysis methods.

3.2.2.4.3 Testing finished products

Due to the way the vermicomposting trial was conducted, finished products from this trial were not specifically covered under the NZS 4454:2005 New Zealand Standard

Compost, Soil Conditioners and Mulches (hereon referred to as the Standard). The Standard covers organic products and mixtures derived largely from compostable organic materials, including pasteurised and composted products.

As only small volumes of final products were produced at lab scale, it was not practical to completely follow the methods outlined in the Standards New Zealand (2005). For final product testing, the methods were adapted for smaller volumes as required. Deviations from the Standard are noted. Test samples from some methods were used for more than one test (providing the previous test would not affect the following tests). In total, about 3 L of finished product were needed for the full suite of testing outlined in Table 3-6. The Standard recommends taking 50 g subsamples to make composite samples for each test, but given the small total volume of finished product, the entire contents were mixed and a composite made up of at least three subsamples taken instead.

There is a recommendation in the foreword of the Standard for the document to be revised every five years and in line with changes to heavy metal and organic contaminant limits under the Biosolids Guidelines (Standards New Zealand, 2005). While no biosolids (defined as “treated organic wastes of human origin” (Water New Zealand, 2025)) are used in any part of this study or the broader thesis, both the original 2003 and the new 2025 limits for heavy metals have been included for comparison to demonstrate compliance with industry-accepted soil limits. The products produced in this trial are technically excluded from the Standard as they were not produced according to the recommended methods, however as (i) this was a lab scale trial and (ii) organic waste management technology has advanced since publication of the Standard, the finished products were still tested against all relevant criteria.

On the final day of the trial, 25 g samples of finished product were taken separately from each tub and submitted for *Escherichia coli* testing. This was done prior to mixing and other sampling to avoid contamination. Bulk density was measured using the method described under Section 3.2.2.3.2. The tub contents were then tipped onto large metal trays in a well-lit area. Material was slowly removed from the tops and edges of the piles and placed back in the tubs, breaking apart clods and removing worms as they were found. Worms were placed in separate containers with paper towels and moistened with distilled water. The paper towels were replaced three times over the following 24-hour period to remove vermicast. Voided worm biomass was measured. The material in the tubs was mixed and the remaining tests in Table 3-6 carried out. These tests were adapted as necessary due to the small volume of material produced.

A subsample of industrially produced vermicast (White Gold) left over from the glasshouse plant production trials (Chapter 4) and also used in the main plant production trials (Chapter 5) was used as a comparison for the main trial products, however not all tests e.g. ICP-MS were performed on this product due to cost.

E. coli testing was chosen for the main trial over enterococci and faecal coliforms. Enterococci were not detected in the DAF sludge in the pilot trial. Both *E. coli* and faecal coliforms are recognised as microbiological quality indicators under the Standards (Standards New Zealand, 2005).

Table 3-6: NZS 4454:2005 recommended tests for vermicast/vermicompost The methods followed are published in the official Standard (Standards New Zealand, 2005). The methods are not repeated in this thesis, however, adaptations due to the small amount of finished product available for testing are stated. EC = electrical conductivity. ICP-MS = Inductively Coupled Plasma – Mass Spectrometry.

Appendix	Test	Volume tested	Comments/adaptations
Microbiological tests			
	E. coli	50 mL	Required as a meat processing residual (Dissolved Air Flotation sludge from chicken processing) was used as inputs. In the Standard, the test can either be for *E. coli* or faecal coliforms. *E. coli* was selected over faecal coliforms as *"at present, the microbiological quality of pathogens in compost is to be determined using an indicator bacteria* E.coli*" (Standards New Zealand, 2005)*. Sample was taken prior to other tests to avoid contamination.
Chemical tests			
A	pH, EC, NH_4^+, NO_3^- and soluble P	200 mL	pH and EC done in-house. Extract for NH_4^+, NO_3^- and soluble P frozen before analysis at Lincoln University. Extracts required centrifuging at 3000 RPM for 10 minutes, filtering though Whatman 42 filter papers and then refiltering through 0.45 µm luer lock syringe filters.
B	C, N and organic matter content	10 mL	Dried, ground samples analysed at Lincoln University (see section 3.2.2.4.2).
C	Total P, B, Ca, Mg and Na	1 mL	Elemental analysis done using reverse aqua regia digestion method, not the method in the Standard. Elements analysed by ICP-MS. Boron required to be tested as cardboard was a component of the feedstock. Additional nutrients, including heavy metals (below) tested. See section 3.2.2.4.2.
-	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn	Combined with above sample.	Combined with above sample (elemental analysis via digestion and ICP-MS). *"Comply with the Biosolids Guidelines a limits… no test methods have been specified for metals… since there are a number of methods that can be used. It is recommended that the USEPA methods are used… or determined using IANZ/AOAC accredited methods" (Standards New Zealand, 2005).*
F	Moisture content	500 mL	Subsample used for quick DM testing prior to toxicity test. Also tested ash content.
-	Organic contaminants	-	*Organic contaminants (DDT/DDD/DDE, aldrin, dieldrin, chlordane, heptachlor, heptachlor expoxide, hexachlorobenzene (HCB) and hexachlorocyclohexane (lindane) were not tested for due to cost.*
Biological tests			
D	Toxicity test	210 mL	French Breakfast radish seeds (100% germination rate, tested prior to trial) were used as Long Scarlett seeds were not available for this test. A Dalton sand control was included for comparison. As well as testing pure product as stipulated, a 12.5 t FM/ha broadcast (surface applied) and 12.5 t FM/ha incorporated treatment were included for each treatment. No replication. Nursery pots 120 mm (not 150 mm) tall were used. Material was sieved to 11.2 mm, not 10 mm. The effect of application method on radish root length was assessed using the seven vermicomposts as replicates (n = 7 per method). Average root length per vermicompost was calculated across the ten seedlings per pot prior to analysis. Homogeneity

Appendix	Test	Volume tested	Comments/adaptations
			of variance was assessed using Levene's test. A one-way ANOVA was performed, followed by Fisher's Least Significant Difference test with Bonferroni adjustment where significant differences were detected ($p < 0.05$).
J	Plant propagules	800 mL	PB5 planter bags (~121 cm^2 surface area 17 cm deep) are stipulated for this test, but shallower trays (5 cm – maximum depth recommended for testing mulches) with greater total surface area (175 cm^2) were used instead. This test was performed after a short storage period.
N	Plant growth index	1,600 mL	*Although not required for vermicasts under the Standard, this test was performed after a short storage period. Dalton's washed sand was not available for this experiment, so a white silica sand was used instead. Three replicates of a sand Control were tested. Due to only a small amount of vermicompost being available, only one replicate of a 1:1 sand:vermicompost mix was trialled for each tub. For each tub, three replicates of a 12.5 t/ha broadcast treatment on sand were tested. A pure vermicompost sample made from the leftover vermicomposts (excluding 6B) was also tested.*
-	Biology	-	*No method recommended: "the biology of compost is vitally important for the release of nutrients contained within the compost. Development of a methodology to determine how this is to be measured is subject to further work" (Standards New Zealand, 2005).*
Physical tests			
E	Particle size grading	500 mL	A mechanical shaker was used for sieving.
G	Volume and mass (bulk density)	500 mL (reused in other tests)	Did not have enough product for recommended method. Instead, bulk density was tested as per the method described under Section 3.2.2.3.2 (after *E. coli* sampling, before disturbance for other testing) and then with a 10 mL graduated jug after worm removal.
Contamination			
P	Glass, metal and hard plastic, stones and lumps of clay, plastics – light, flexible or film	500 mL (used sample from moisture content determination)	A mechanical shaker was used for sieving. Material was sieved using a 4.75 mm, rather than 5 mm sieve.
Q	Large particles	600 mL	A 1 L, 20 mL graduated beaker with 123 mm internal diameter and 126 mm height was not available. A 1 L jug with 50 mL graduations of similar dimensions was used instead.

3.3 Results

3.3.1 Pilot trial

3.3.1.1 Enterococci test results

The result for the initial DAF sludge enterococci test was <10 colony forming units (cfu)/g. This is an indication that the DAF sludge was sanitary prior to the beginning of the trial. No final product (vermicast or compost) samples were tested as there would not have been any detectable reduction in pathogen count.

3.3.1.2 Input and feedstock characteristics

Elemental analysis via ICP-MS and C:N analysis indicated that the DAF sludge was the major source of nutrients, while the cardboard was the major source of carbon (Table 3-7). The listed major and minor plant elements were detected in all samples, although in some cases not above their respective quantitation limits (QL) in the inputs and feedstocks. Though their accuracy is lesser than results detected above QL, these results are still reported as they demonstrate the DAF sludge supplied most of the nutrients in the vermicomposting feedstocks. Nitrogen, followed by P, Al and S (below QL) were the most abundant nutrients in the DAF sludge. Calcium followed by N, Al and S (below QL) were the most abundant nutrients in cardboard. B was not detected in any sample.

Feedstock input pH, EC and ash content are reported in Table 3-8. Increasing the cardboard content had little effect on pH, though EC and ash content declined, indicating lower salt and mineral contents in the cardboard than the DAF sludge.

Heavy metal concentrations were compared to the 2003 Guidelines for the safe application of biosolids to land in New Zealand, as referred to in the 2005 New Zealand Standards for Composts, soil conditioners and mulches (New Zealand Water and Wastes Association, 2003; Standards New Zealand, 2005). As the biosolids guidelines have been updated since the 2003 version, these (higher) limits have also been included in Table 3-9. Except for cadmium (Cd), which was detected below quantitation limits, none of the limits for heavy metals were approached or exceeded by the inputs or feedstocks.

Table 3-7: Major and minor plant nutrients detected in inputs and feedstocks. Results reported in mg/kg DM. *Italicised* results are below quantitation limits. ND = not detected. DAF = Dissolved Air Flotation sludge from chicken processing. Feedstock ratios are the quantity of cardboard mixed with DAF sludge.

	DAF	**2:1**	**3:1**	**4:1**	**Cardboard**
Major plant nutrients					
N	55,883	18,377	12,963	11,034	1,085
P	22,174	4,523	4,303	3,481	32
K	*1,375*	*528*	*375*	*289*	*78*
S	*3,351*	*1,089*	*1,222*	*697*	*278*
Ca	*2,161*	10,303	10,894	10,955	12,893
Mg	571	421	367	346	298
Minor plant nutrients					
Al	18,819	5,774	4,034	3,286	481
B	ND	ND	ND	ND	ND
Co	*0.48*	*0.44*	*0.34*	*0.40*	*0.36*
Fe	940	594	500	475	447
Na	720	458	334	286	*182*
Mn	116	51	42	37	22

Table 3-8: pH, electrical conductivity (EC) and ash content of pilot trial feedstock inputs.

Parameter	**Treatment**				
	DAF	**2:1**	**3:1**	**4:1**	**Cardboard**
pH	5.89	5.8	5.8	5.82	6.98
EC (dS/m)	3.6	1.9	1.7	1.3	0.5
Ash content (%)	21.7	10.2	9.2	8.6	6.2

Table 3-9: Heavy metal contents detected in inputs and feedstocks, compared to the limits for land application of biosolids in New Zealand (New Zealand Water and Wastes Association, 2003; Water New Zealand, 2025). Results reported in mg/kg DM. ND = not detected. *Italicised* results are below quantitation limits. DAF = Dissolved Air Flotation sludge from chicken processing. Feedstock ratios are the quantity of cardboard mixed with DAF sludge.

Element	**Treatment**					**Application limits**	
	DAF	**2:1**	**3:1**	**4:1**	**Cardboard**	**2003**	**2025**
As	*0.02*	0.05	*0.02*	ND	ND	20	30
Cd	*10.70*	*9.61*	*9.22*	*8.61*	*8.49*	3	6.5
Cr	3.16	9.10	5.53	7.84	16.42	600	1,500
Cu	26.02	15.41	13.97	12.58	10.32	300	750
Pb	*0.14*	*1.20*	*1.42*	*1.21*	*1.46*	250	300
Hg	Not tested					2	7.5
Ni	*2.09*	*1.99*	*1.18*	*1.10*	0.97	60	135
Zn	13.58	13.54	12.74	12.51	12.55	600	1,250

3.3.1.3 Final product (vermicast/compost) characteristics

Excluding the pure DAF treatments, both vermicomposting and composting at least doubled the concentration of most elements in the final products compared to the initial feedstocks (Table 3-7 versus Table 3-10). Except for N, vermicomposting concentrated elements more than composting alone (i.e. without worms). Sulphur, potassium, cobalt and sodium showed the greatest increase in concentration between feedstocks and final products, though except for sodium these elements were not detected above their respective QL in any final product. The pure DAF treatment for vermicomposting was toxic to worms throughout the trial, and it appeared to process in a very similar way to the composted (no worms) treatment. This is seen in the similar values for each nutrient between both final DAF products. Both calcium and sodium contents increased with increasing cardboard content in the final products, indicating the cardboard was the major source of these nutrients. All other nutrients increased with increasing DAF content, indicating they were supplied by the DAF sludge.

Heavy metal concentrations appeared to increase more in treatments with higher cardboard contents, regardless of worm presence. Cadmium had increased 2.3 fold on average for both composted and vermicomposted feedstocks and well exceeded both the 2003 and 2005 limits, though it was still below quantitation limits for the analysis. None of the other New Zealand biosolids application limits were approached for any heavy metal in any treatment (Table 3-11).

3.3.1.4 Inoculation

The initial inoculation on 17 October 2024 failed as all worms in all treatments died. Feedstock was assumed to be too ‘fresh’ and a combination of factors may have contributed to the initial inhospitable nature of the feedstocks e.g. NH_3 and NH_4^+ contents, EC. It was determined that a pre composting period was required before reinoculation. The second attempt (referred to as ‘Inoculation’ from hereon) on 5 December 2024 was partially successful as the DAF sludge treatments containing cardboard were able to support some, if not all adult worms added to the treatments. Worms introduced to the pure DAF treatments did not survive. Reinoculation of the pure DAF treatments was attempted each subsequent month. No worms survived in the pure DAF treatments at any stage of the experiment, with some dying within hours of inoculation attempts. Refer to Figure 3-3 and Table 3-12.

Table 3-10: Major and minor plant nutrients detected in final products (vermicast/compost). Results reported in mg/kg DM. *Italicised* results are below quantitation limits. ND = not detected. DAF = Dissolved Air Flotation sludge from chicken processing. Feedstock ratios are the quantity of cardboard mixed with DAF sludge.

	Vermicomposted (vermicast/vermicompost)				**Composted (compost)**			
	DAF	**2:1**	**3:1**	**4:1**	**DAF**	**2:1**	**3:1**	**4:1**
Major plant nutrients								
N	55,373	38,266	31,524	30,520	57,092	42,056	37,550	34,257
P	34,865	13,892	11,718	9,187	34,253	14,308	10,850	8,285
K	*2,327*	*1,174*	*1,263*	*934*	*2,110*	*1,133*	*1,057*	*892*
S	*4,506*	*3,200*	*3,673*	*2,838*	*4,451*	*3,523*	*3,319*	*2,035*
Ca	3,940	24,238	30,193	32,328	3,780	24,446	28,683	29,718
Mg	847	740	771	766	808	710	721	676
Minor plant nutrients								
Al	26,286	11,147	9,443	7,849	25,703	11,263	8,780	7,007
B	ND	ND	ND	ND	ND	ND	ND	ND
Co	*0.99*	*1.04*	*1.20*	*1.29*	*0.97*	*1.04*	*1.08*	*1.01*
Fe	1,702	1,220	1,279	1,156	1,704	1,245	1,214	1,103
Na	824	941	1,087	1,023	679	848	914	748
Mn	204	120	115	105	206	124	109	97

Table 3-11: Heavy metal contents detected in final products (vermicast/compost), compared to the limits for land application of biosolids in New Zealand (New Zealand Water and Wastes Association, 2003; Water New Zealand, 2025). Results reported in mg/kg DM. ND = not detected. *Italicised* results are below quantitation limits. DAF = Dissolved Air Flotation sludge from chicken processing. Feedstock ratios are the quantity of cardboard mixed with DAF sludge.

	Vermicomposted (vermicast/vermicompost)				Composted (compost)					
	DAF	**2:1**	**3:1**	**4:1**	**DAF**	**2:1**	**3:1**	**4:1**	**2003 limits**	**2025 limits**
As	*0.07*	*0.09*	*0.09*	*0.12*	*0.05*	*0.05*	*0.11*	*0.02*	20	30
Cd	*18.8*	*21*	*24*	*24*	*18*	*23*	*23*	*22*	3	6.5
Cr	7.89	3.95	4.07	4.45	5.46	4.11	4.08	8.13	600	1,500
Cu	48	36	37	36	49	37	36	34	300	750
Pb	0.*30*	2.75	3.49	3.60	*0.33*	2.77	3.34	3.45	250	300
Hg				Not tested					2	7.5
Ni	4.49	2.80	2.54	*2.36*	4.56	2.81	2.29	3.65	60	135
Zn	24	31	35	36	24	33	34	33	600	1,250

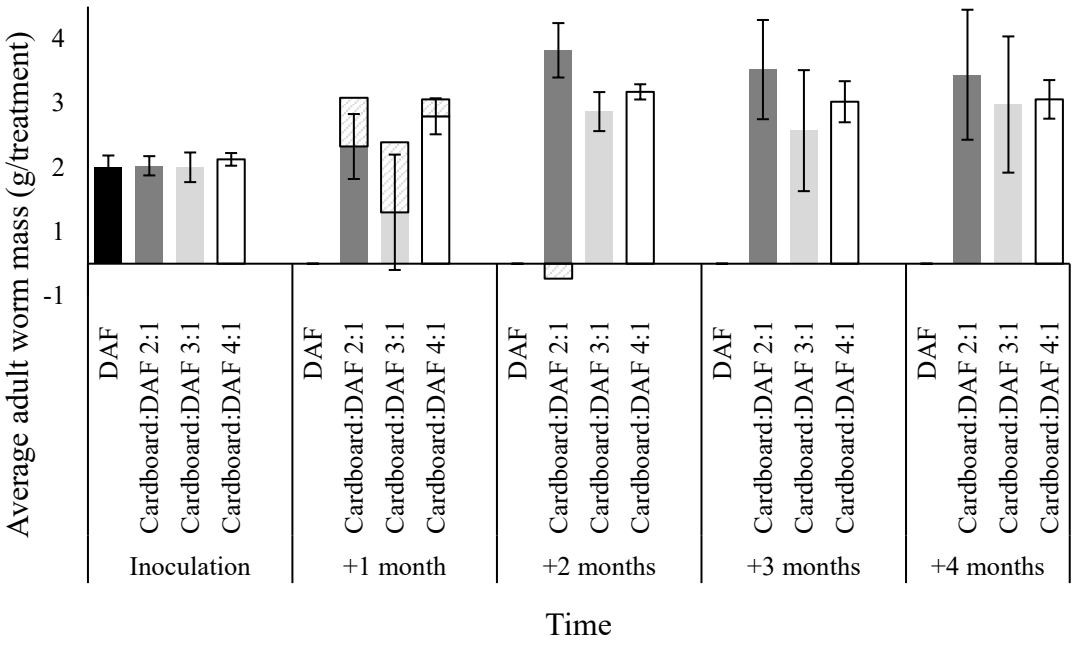


Figure 3-3: Average total adult worm mass from the first successful inoculation to the end of the pilot vermicomposting trial. Inoculation date was 5 December 2024. Worm biomass added at Inoculation is represented by solid bars. Worm biomass 'added' after Inoculation is represented by shaded bars with black outlines 1 month post inoculation. Black bars represent DAF sludge, dark grey the 2:1 treatments, light grey the 3:1 treatments and white with black outline the 4:1 treatments. Error bars are standard deviation. DAF = dissolved air flotation sludge.

3.3.1.5 Adult worm biomass and population

In early January (+1 month post Inoculation), unvoided worms were added as per Table 3-12 as not all worms had survived the initial inoculation. In late January (+2 months post Inoculation), all worms in the Cardboard:DAF treatments had survived, and an extra worm (accidentally added the previous month) found in one of the 3:1 replicates was removed. Because of the small scale of this trial, it was decided that worms added after the initial inoculation date would be unvoided to minimise stress. Despite all Cardboard:DAF treatments demonstrating they could support 100% of the adult population, replacements were not made more than +1 month post Inoculation as final stocking rate was potentially a treatment effect.

At the conclusion of the experiment, the pure DAF treatment was excluded from the ANOVA. Total worm biomass and average worm biomass for the Cardboard:DAF treatments resulted in similar statistical outcomes (Table 3-13). After four months of vermicomposting, one-way ANOVA showed no statistically significant differences in total or average worm biomass per treatment between the Cardboard:DAF treatments. Though mild heteroscedasticity was present in the residual plots, further assumption checks using the Shapiro-Wilk test showed the model residuals were normally distributed and Levene's test showed the variances were homogeneous, supporting the validity of the

ANOVA. A non-parametric Kruskal-Wallis test supported the conclusion of no statistically significant differences among treatments, while indicating a possible trend given the marginal p-value in the total worm biomass. A log transformation was also tried and gave similar results (not reported).

Table 3-12: Number of live worms over vermicomposting period. Numbers in brackets are the number of worms added to bring the total number of worms to the original stocking rate of five per replicate.

Treatments	Rep.	5/12/2024 Inoculation	6/01/2025 +1 month	31/01/2025 +2 months	27/02/2025 +3 months	27/03/2025 +4 months
DAF	1	5	0 (0)	0	0	0
DAF	2	5	0 (0)	0	0	0
DAF	3	5	0 (0)	0	0	0
Cardboard:DAF 2:1	1	5	3 (2)	6 (-1)	4	3
Cardboard:DAF 2:1	2	5	2 (3)	5	5	5
Cardboard:DAF 2:1	3	5	4 (1)	5	4	4
Cardboard:DAF 3:1	1	5	0 (5)	5	5	5
Cardboard:DAF 3:1	2	5	5 (0)	5	5	5
Cardboard:DAF 3:1	3	5	1 (4)	5	2	2
Cardboard:DAF 4:1	1	5	4 (1)	5	4	4
Cardboard:DAF 4:1	2	5	4 (1)	5	4	4
Cardboard:DAF 4:1	3	5	5 (0)	5	4	4

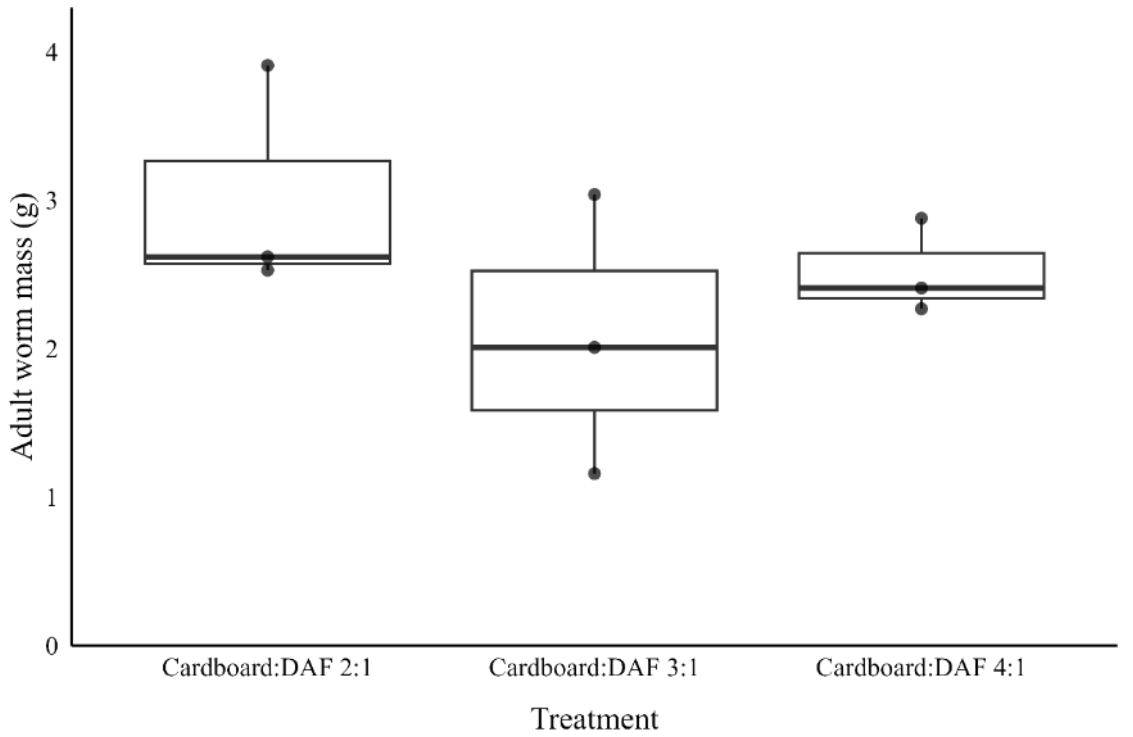


Figure 3-4: Adult worm mass per treatment (unvoided) at the conclusion of the pilot trial, four months after inoculation. Note these masses include gut fill. DAF = dissolved air flotation sludge. N.B. pure DAF treatment not included.

Table 3-13: Results for statistical analysis of final (unvoided) worm biomass.

	Total treatment worm biomass	**Average treatment worm biomass**
ANOVA	F(2,6) = 0.247, p = 0.789	F(2,6) = 1.444, p = 0.308
Shapiro-Wilk test	W = 0.952, p = 0.712	W = 0.881, p = 0.163
Levene's test	F(2,6) = 0.786, p = 0.497	F(2,6) = 0.009, p = 0.991
Kruskal-Wallis	Chi-squared = 6.53, p = 0.089	Chi-squared = 1.87, p = 0.393

There was considerable variability in worm survival within treatments. In the month following inoculation, two of the 4:1 Cardboard:DAF replicates had lost 1 worm each, while comparatively, two of the 3:1 replicates had lost 4 and 5 worms each, and the 2:1 replicates lost 1, 2 and 3 worms each. By the end of the four-month vermicomposting period, the 4:1 Cardboard:DAF treatment demonstrated the lowest variability in worm biomass and adult worm numbers.

The bioconversion efficiency (BE) of the worms in each treatment was estimated using (Bosch *et al.*, 2020):

$$Bioconversion\ efficiency\ (BE\%) = \left(\frac{Final\ worm\ mass\ (g) - Initial\ worm\ mass\ (g)}{Initial\ feed\ mass\ (g)}\right) \times 100$$

The 2:1 treatment had the highest BE (average 72 ± 7%), whereas the 3:1 and 4:1 treatments had similar BEs (63 ± 8% and 64 ± 8% respectively). Note that gut fill was included in these calcualtions.

3.3.1.6 Capsules and juveniles

The number of juvenile *E. fetida* worms was not significant after four months of vermicomposting. The results of an ANOVA F(2,6) = 3.316, p = 0.107 indicate that there was no significant difference between the Cardboard:DAF treatments despite the biologically meaningful difference (four to nine times) between the means of the 4:1 treatment compared to both the 2:1 and 3:1 treatments (Figure 3-5).

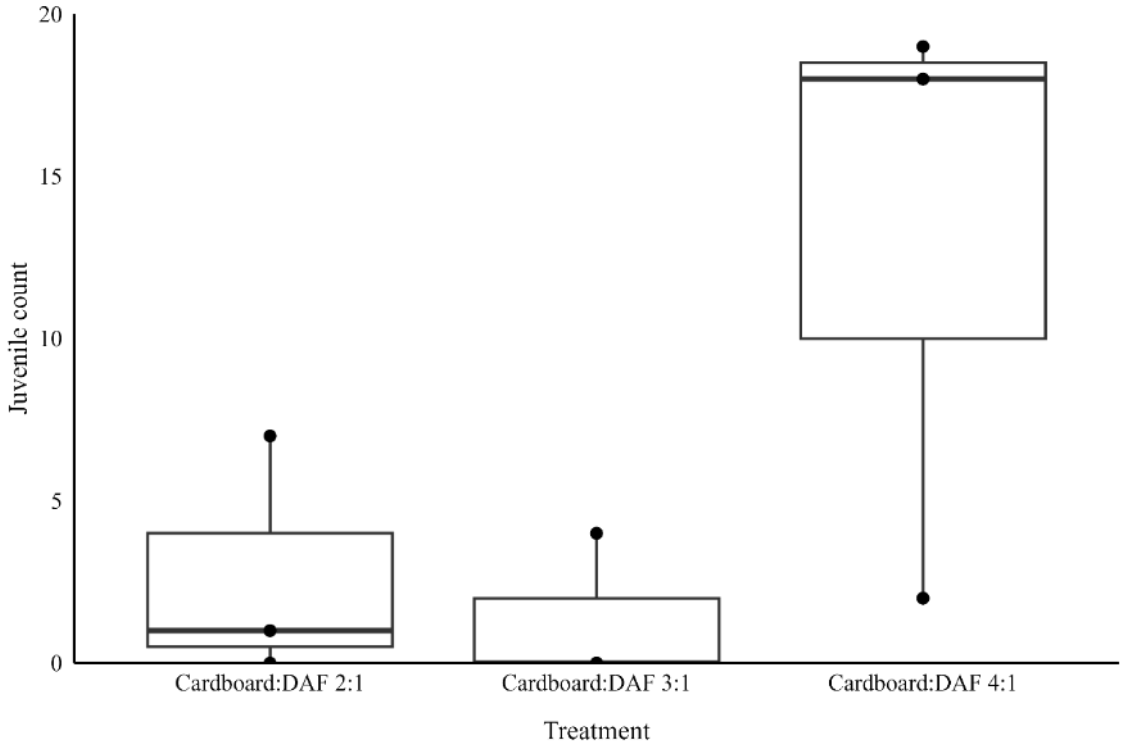


Figure 3-5: Juvenile worm count at the conclusion of the pilot trial, four months after inoculation. DAF = dissolved air flotation sludge. N.B. pure DAF treatment not included.

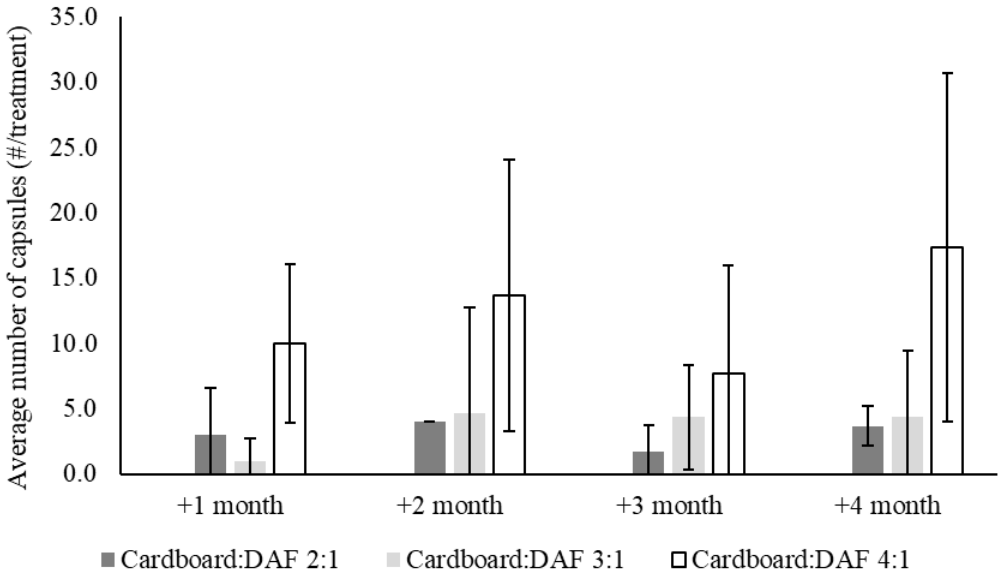


Figure 3-6: Average unhatched capsules monthly after inoculation (5 December 2024). Y-axis was truncated at 0. Error bars are standard deviation. DAF = dissolved air flotation sludge.

3.3.1.7 Feedstock processing

Treatments with worms processed faster, as indicated by the appearance of the material at the conclusion of the experiment. By the third month post inoculation, the Cardboard:DAF 4:1 vermicomposting treatments appeared to be close to finishing, with "some cardboard still visible". By the conclusion of the pilot trial (four months post inoculation), the 4:1 treatments with worms and one of the replicates without worms

appeared to be finished, with only some fine cardboard fibres remaining in the vermicast. By the end of the experiment, the 3:1 and 2:1 treatments with worms were mostly processed, but cardboard fibres were still visible. Treatments without worms still had pieces of carboard visible within the final month of whereas their counterparts with worms only had fibres rather than pieces of cardboard visible. The pure DAF treatments tended to form a firm orange skin on the surface exposed to air, with the interior remaining grey, indicating a lack of oxygen. On November 8th 2024, a porous texture was noted on in the DAF sludge of one of the pure DAF composting treatments. Maggots were identified as the cause on November 22 2024. The species of fly was not identified, but inoculation was most likely to have occurred at the initiation of the trial as once the trial started, the feedstocks were not accessible to large insects such as house or blow flies.

Table 3-14: Average dry matter (DM) loss throughout trial. DAF = Dissolved air flotation sludge. NW = no worms.

Treatment	**Initial DM**	**Average final DM**	**Average DM loss**		**Significance**
	(g)	**(g)**	**(g)**	**%**	**group letters**
DAF	50.00	23.38	26.62	53%	a
Cardboard:DAF 2:1	50.00	17.21	32.79	66%	bc
Cardboard:DAF 3:1	50.00	16.92	33.08	66%	bc
Cardboard:DAF 4:1	50.00	16.43	33.57	67%	c
DAF NW	50.00	23.25	26.75	54%	a
Cardboard:DAF 2:1 NW	50.00	18.80	31.20	62%	b
Cardboard:DAF 3:1 NW	50.00	18.14	31.86	64%	bc
Cardboard:DAF 4:1 NW	50.00	18.20	31.80	64%	bc

All replicates started out with 50 g DM of either pure DAF or a mixture of Cardboard and DAF. BY the end of the trial, except for the pure DAF treatments, most of the DM had been lost (Table 3-14). ANOVA results indicated significant differences between the final DM of treatments ($p = 2.04 \times 10^{-9}$). A Tukey HSD test identified 13 out of the 28 possible treatment pairs as significantly different. Treatment means were assigned significant letters and are shown in Figure 3-7.

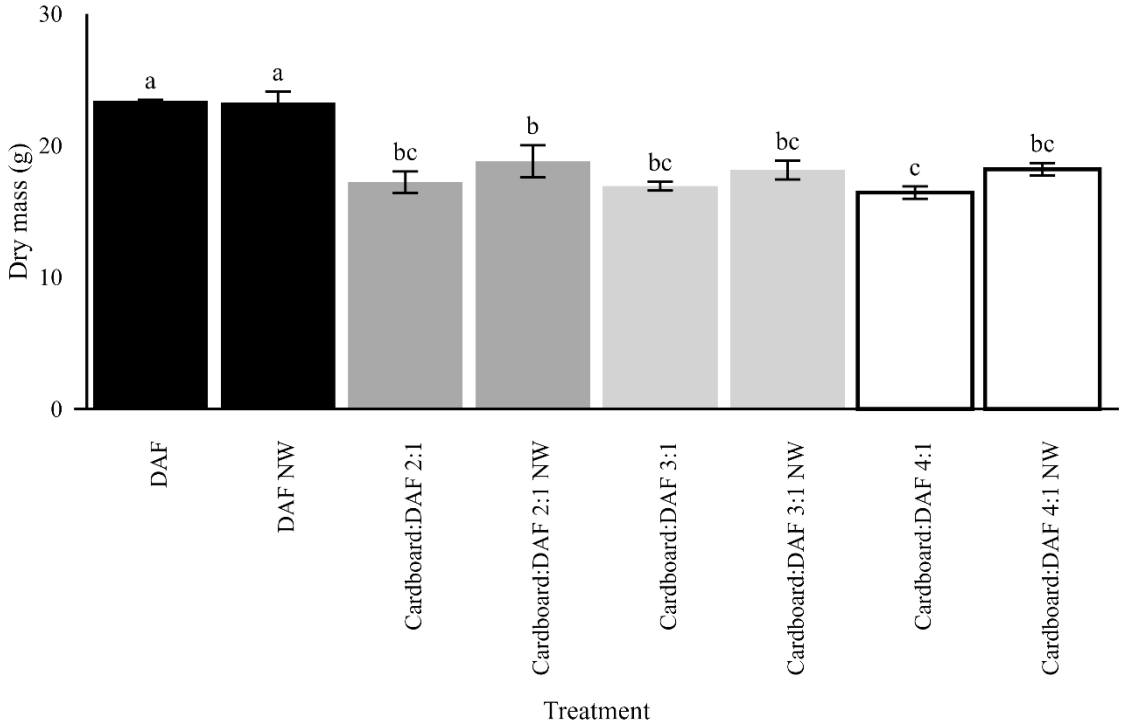


Figure 3-7: Average dry mass of material (unprocessed feedstock/compost/vermicast) at the conclusion of the pilot trial. Error bars are standard deviation. DAF = dissolved air flotation sludge. NW = no worms. Letters above bars are significance group letters based on the Tukey HSD test.

Pure DAF treatments were significantly different to all treatments with cardboard mixed into the feedstock. Vermicomposting treatments (excluding pure DAF) appeared to have lower final DM than their composting counterparts, though these differences were not significantly different.

Except for both Cardboard:DAF 2:1 treatments (with and without worms) and Cardboard:DAF 3:1 NW, the pure DAF treatments were significantly different to all other treatments. Vermicomposting treatments (excluding pure DAF) appeared to have higher final pHs than their composting counterparts, though these differences were not significantly different. The only other treatments that differed in final pH were the Cardboard:DAF 4:1 (with worms) and the 2:1 without worms.

Electrical conductivity was tested on the final samples, but most were outside the detectable range (2 dS/m). Two readings were obtained: 1.9 dS/m from a 4:1 Cardboard:DAF replicate with worms and 1.6 dS/m from a 4:1 Cardboard:DAF without worms.

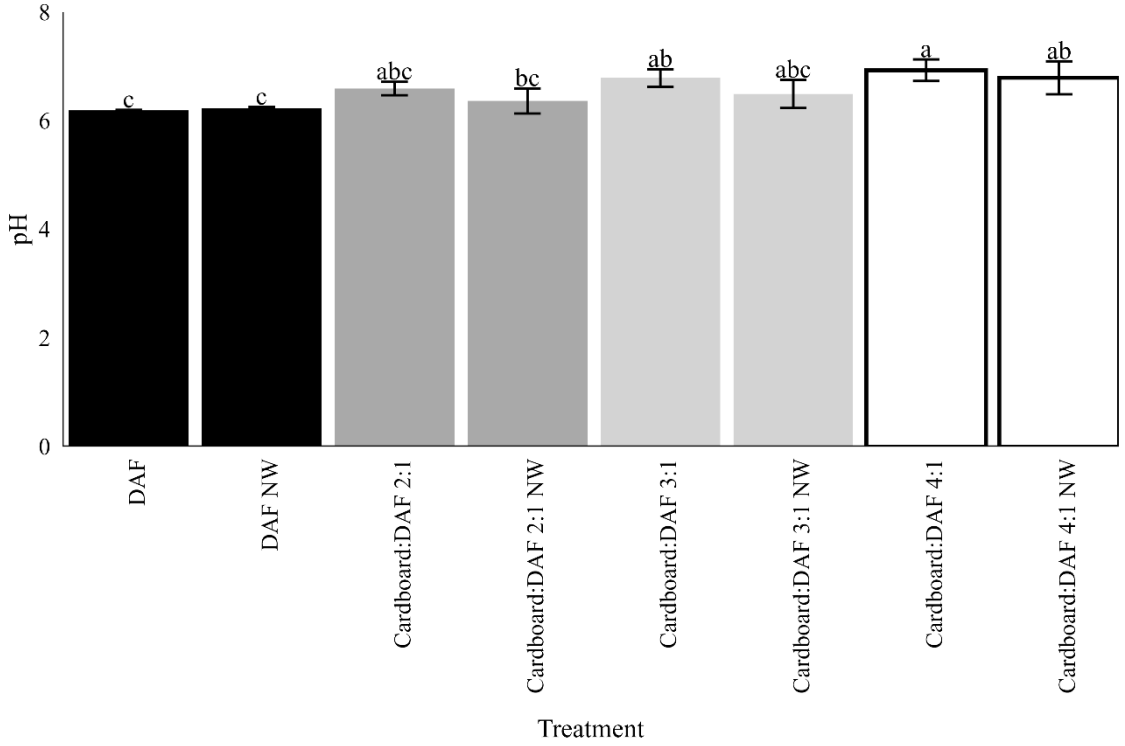


Figure 3-8: Average pH of material (unprocessed feedstock/compost/vermicast) at the conclusion of the pilot trial. Error bars are standard deviation. DAF = dissolved air flotation sludge. NW = no worms. Letters above bars are significance group letters based on the Tukey HSD test.

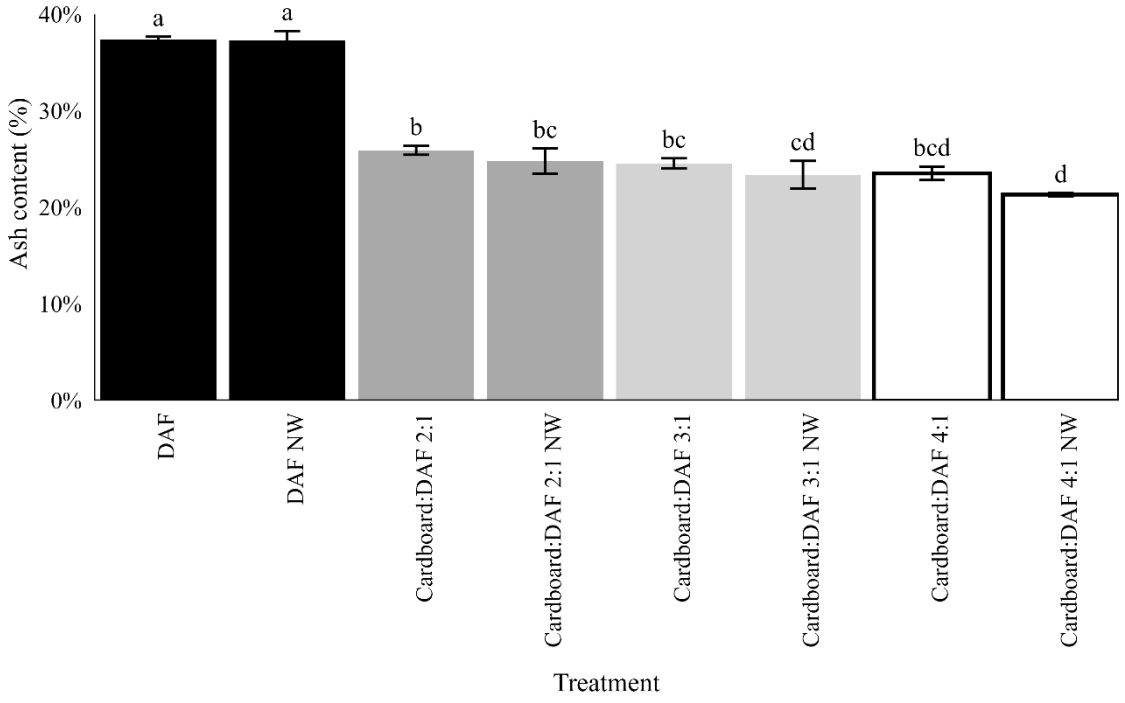


Figure 3-9: Average ash content of material (unprocessed feedstock/compost/vermicast) at the conclusion of the pilot trial. Error bars are standard deviation. DAF = dissolved air flotation sludge. NW = no worms. Letters above bars are significance group letters based on the Tukey HSD test.

Ash content of the final products varied between the DAF sludge and the Cardboard:DAF treatments (Figure 3-9). This is not surprising as the initial ash contents

of the DAF sludge was about three times higher than that for the cardboard (Table 3-8). The composted and vermicomposted DAF treatments both had significantly higher ash contents than any of the other feedstocks, indicating lower volatile solids and higher mineral contents. The more cardboard was present in the feedstock, the lower the final ash content. It was also noted that the treatments with *E. fetida* had slightly lower final ash content than their counterpart composting treatments.

Figure 3-10: Cardboard and DAF prior to mixing as feedstock at trial initiation.

Figure 3-11: Maggots and porous texture of contaminated DAF replicate, 6 weeks after trial initiation.

Figure 3-12: Composting (no worms) Cardboard:DAF 3:1 treatment at conclusion of pilot trial. Image shows 'mealy' texture of fungus gnat frass. Cardboard pieces still visible too (see centre of image). Yellow scale bar = 10 cm.

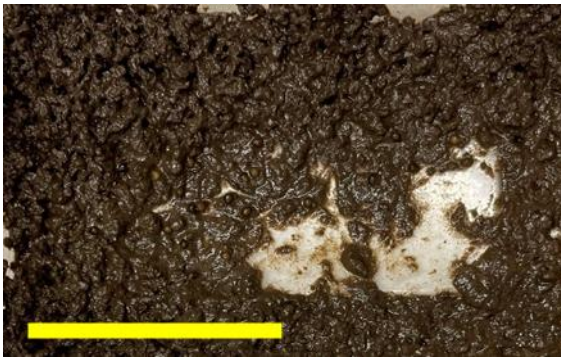


Figure 3-13: Vermicast of Cardboard:DAF 4:1 treatment at conclusion of pilot trial. *E. fetida* vermicast is coarser than fungus gnat frass (Figure 3-12). No cardboard pieces visible. Yellow scale bar = 10 cm.

3.3.1.8 Other observations

Fungus gnats were commonly found around and in the treatment containers. They were first recorded on November 8th 2024 in one of the DAF treatments though throughout the duration of the trial, they were found in all treatments. From about one month after inoculation, the texture of some treatments was described as 'mealy'. The mealy material was fine and fluffy as was determined to be fungus gnat frass. This texture

is quite distinct from *E. fetida* castings, which are coarser. The first treatments to display this texture were two of the 2:1 and one of the 3:1 composting treatments. This was presumed to be caused by the fungus gnats consuming and breeding in the feedstock. Overall, fungus gnat frass was more likely to be found in composting than vermicomposting treatments and more likely to occur in the 2:1 and 3:1 treatments (only one 4:1 composting treatment displayed this mealy texture).

A variety of moulds were noted on all treatments throughout the trial, though there did not appear to be a link between appearance of moulds and treatment.

Ambient temperature ranged between 11.4 and 30.9 °C throughout the vermicomposting period.

3.3.2 Main trial

3.3.2.1 Input and feedstock characteristics

Elemental analysis via ICP-MS and C:N analysis indicated that the DAF sludge was the major source of nutrients, while the cardboard was the major source of carbon (Table 3-15). Though they were tested for and found to be present in the samples, not all major and minor plant elements were detected above their respective quantitation limits (QL) in the inputs and feedstocks. Though their accuracy is lesser than results detected above QL, these results are still reported as they demonstrate the DAF sludge supplied most of the nutrients in the vermicomposting feedstocks. Phosphorus, followed by aluminium and sulphur were the most abundant nutrients in the DAF sludge. Calcium (below QL) followed by sulphur (below QL) and aluminium were the most abundant nutrients in cardboard. Potassium was not detected in pure cardboard though it was detected in samples containing DAF, but below the quantitation limits. Na and B were not detected in any sample.

Heavy metal concentrations were compared to the 2003 Guidelines for the safe application of biosolids to land in New Zealand, as referred to in the 2005 New Zealand Standards for Composts, soil conditioners and mulches (New Zealand Water and Wastes Association, 2003; Standards New Zealand, 2005). As the biosolids guidelines have been updated since the 2003 version and the Standards, these (higher) limits have also been included in Table 3-16. None of the limits for heavy metals were approached or exceeded by the feedstocks. The DAF sludge appeared to exceed both the 2003 and 2005 limits for Cd, though this was detected below quantitation limits. Cadmium was not detected in the cardboard.

Table 3-15: Major and minor plant nutrients detected in inputs and feedstocks. Results reported in mg/kg DM. *Italicised* results are below quantitation limits. ND = not detected. DAF = Dissolved Air Flotation sludge from chicken processing. Feedstock ratios are the quantity of cardboard mixed with DAF sludge.

	DAF	**2:1**	**3:1**	**4:1**	**Cardboard**
Major plant nutrients					
N	66,765	21,635	17,798	15,730	6,889
P	13,066	4,393	3,138	2,714	37
K	*1,029*	*243*	*118*	*101*	ND
S	*3,516*	*1,181*	*1,057*	*1,255*	*480*
Ca	*1,457*	*1,776*	*1,702*	*1,912*	*2,013*
Mg	636	268	*227*	*201*	*88*
Minor plant nutrients					
Al	6,686	2,384	1,757	1,569	373
B	ND	ND	ND	ND	ND
Co	*0.40*	*0.17*	*0.15*	*0.14*	*0.07*
Fe	875	461	409	409	205
Na	ND	ND	ND	ND	ND
Mn	54	25	21	20	9.75

Table 3-16: Heavy metal contents detected in inputs and feedstocks, compared to the limits for land application of biosolids in New Zealand (New Zealand Water and Wastes Association, 2003; Water New Zealand, 2025). Results reported in mg/kg DM. ND = not detected. *Italicised* results are below quantitation limits. DAF = Dissolved Air Flotation sludge from chicken processing. Feedstock ratios are the quantity of cardboard mixed with DAF sludge.

	DAF	**2:1**	**3:1**	**4:1**	**Cardboard**	**2003 limit**	**2025 limit**
As	*0.02*	ND	ND	ND	ND	20	30
Cd	*14.5*	ND	ND	ND	ND	3	6.5
Cr	3.89	7.87	9.19	11.1	5.28	600	1,500
Cu	29	12.2	10.3	9.17	3.81	300	750
Pb	*0.90*	*0.44*	*0.52*	*0.49*	*1.00*	250	300
Hg	ND	ND	ND	ND	ND	2	7.5
Ni	2.37	*1.12*	*1.11*	*1.12*	*0.90*	60	135
Zn	9.27	4.91	4.46	4.19	*2.86*	600	1,250

Figure 3-14 shows that although the cardboard had a higher pH than the DAF sludge, the ratio of cardboard to DAF sludge had no immediate effect on feedstock pH. However, increasing the ratio of cardboard decreased the EC of the feedstock. Initial pH in the feedstocks would have been tolerable for *E. fetida*, however, the EC may have been too high (raw data in Table 8-1).

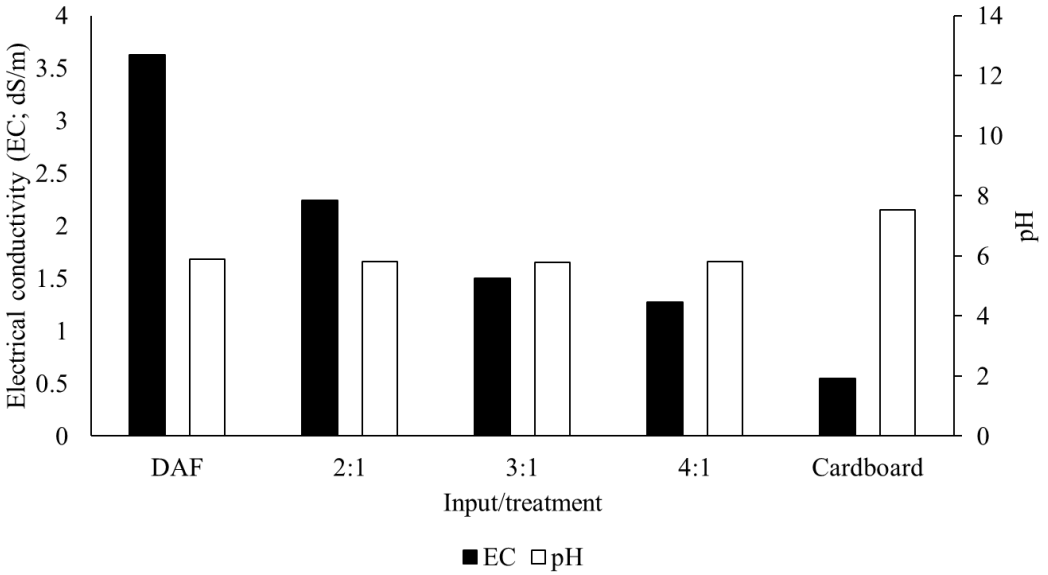


Figure 3-14: Raw inputs and feedstock electrical conductivity (EC) and pH at Week 0 (trial initiation). DAF = chicken processing dissolved air flotation sludge. Ratios are Cardboard:DAF on a dry matter basis.

3.3.2.2 Feedstock inoculation

Initially, the feedstock pHs would have been tolerable for the worms, but the initial EC was too high in all Cardboard:DAF feedstocks. As no worms survived initially in the pilot trial (see Section 3.3.1.4), a seven-week pre composting period was employed prior to inoculating the feedstocks. The odour of NH_3 was detectible in all tubs in Week 5. The addition of five worms to each tub in Week 5 indicated that most feedstocks were not yet acceptable as over the following week worms only survived in 3A and 6B (the two 4:1 Cardboard:DAF treatments). In Week 7, two capsules were visible on the surface of the feedstock in Tub 6B, indicating the worms were breeding. The 2:1 and 3:1 feedstocks (Tubs, 1A, 2A, 4B and 5B) were reinoculated with another five worms in Week 7. By Week 8, there was an indication that Tub 4B (one of the 2:1 treatments) was acceptable to *E. fetida* as two live worms were found in the feedstock. Inoculation socks were then prepared and tubs inoculated as per Section 3.2.2.3.1. The inoculation socks gave the worms a suitable environment to live in until they found the feedstocks acceptable for habitation and the inoculation socks could be removed. By Week 10 (within one week), the worms had moved into tubs 3A, 5B and 6B (both 4:1 and one 3:1 treatments, see photo R in Figure 3-23). At this stage, the odour of NH_3 was detectable in tubs 1A, 2A and 4B. Worms moved into the feedstocks in Tub 2A in Week 12 and into Tub 4B in Week 15. Tub 1A took much longer than the other feedstocks, with worms only moving into the feedstock in Week 27.

3.3.2.3 Leachate impacts

Dry matter loss due to decomposition was not taken into account in the watering regime. From the point worms moved out of the inoculation socks and into the feedstocks, water was no longer mixed into the feedstocks to avoid damaging the worms. The combination of these factors led to the accumulation of leachate in the bottom of the tubs and subsequently made the feedstocks unfavourable – in later weeks, worms would sometimes try to escape after watering and it was not uncommon to find dead worms on the surface of the feedstocks in later weeks. Some worms were found with damage to the lower halves of their bodies as if segments had been cinched. From Week 11, NH_3 presence was tested. From Week 18 to Week 26, water application was restricted to misting the surface of the tubs only, but the volume of water was increased. From Week 27 to Week 35, 10% of weekly FM loss was applied to each tub.

This was a change from replacing all water lost in the previous week/aiming to maintain a high moisture content. Despite the impact of the leachate on worm health, worm populations survived in all tubs (Figure 3-15; raw data in Table 8-2). However, by Week 40, only about half the original worm biomass (average 67 g) was recovered in each tub (note this is an approximation as the original worm biomass added (250 worms, ~150 g) were unvoided). See photos G-I in Figure 3-23.

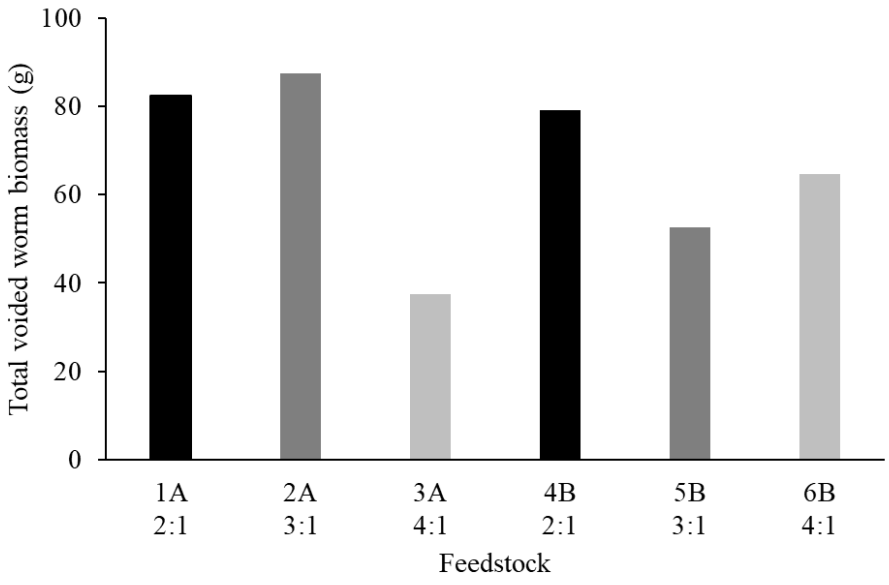


Figure 3-15: Main trial final worm biomass after 40 weeks vermicomposting. Tub labels and ratio of cardboard to DAF sludge are given.

3.3.2.4 Weekly feedstock monitoring

Feedstock mass (measured weekly prior to watering) remained constant until Week 19 (Figure 3-16). By the end of the trial, the FM had reduced by about half. The

initial feedstock moisture content (74%) was similar to the final average moisture content of 75.2% (Table 3-17). Interestingly, although the feedstocks had very similar moisture contents ranging from 71.4-77.7%, there was a noticeable difference in surface wetness where treatments 3A, 5B and 6B felt less sticky than 1A, 2B and 4B.

The rapid decline in total mass after Week 19 is likely due to evaporation of the leachate after the watering schedule was changed in Week 18.

Table 3-17: Initial dry matter (DM) and moisture contents (MC) for initial and final feedstocks.

Treatment	Initial		Final	
	DM%	MC%	DM%	MC%
1A 2:1 Cardboard:DAF	73.5	26.5	23.7	76.3
2A 3:1 Cardboard:DAF			23.1	76.9
3A 4:1 Cardboard:DAF			27.2	72.8
4B 2:1 Cardboard:DAF			23.5	76.5
5B 3:1 Cardboard:DAF			22.9	77.1
6B 4:1 Cardboard:DAF			28.6	71.4

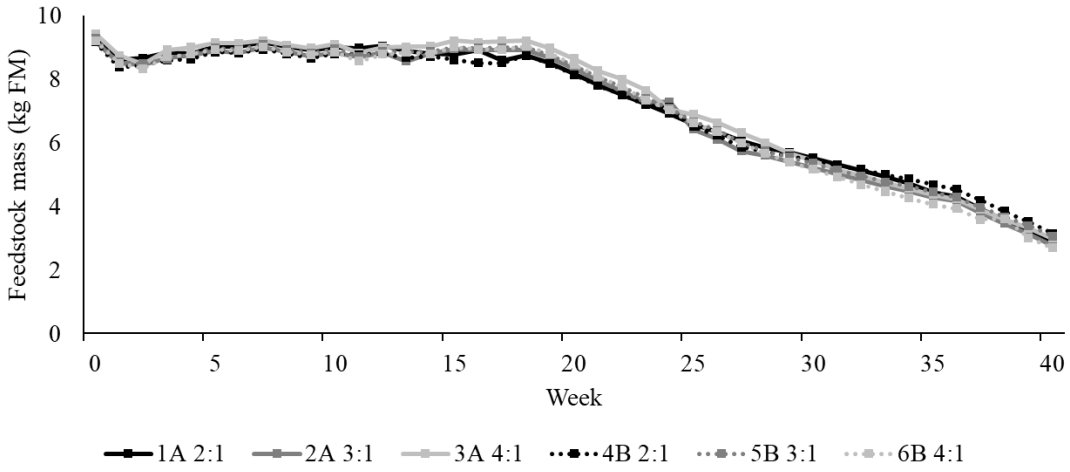


Figure 3-16: Main trial weekly feedstock total fresh matter (FM). Tub labels and ratio of cardboard to DAF sludge are given in the figure legend.

Feedstock height and bulk density were not measured prior to Week 8. Bulk density (BD) varied most in the earliest weeks measured. Feedstock bulk density sat around 700 g/L from Week 8-35 and dropped to an average of 444 g/L in Week 37, after Week 36 mixing and finally to 370 g/L in Week 40. Feedstock height declined from an average of 104 mm at Week 8 to 46 mm in Week 35. In Week 37, it increased to 57 mm post mixing and finally to 45 in Week 40.

After Week 18, BD in all treatments declined, similarly with feedstock mass (Figure 3-16 and Figure 3-17). As feedstock mass declined, so did feedstock height (used

to calculate BD). As well as evaporation explained earlier, decomposition/vermicomposting would also have been occurring throughout the trial, contributing to the feedstock mass loss and reduction in bulk density. All treatments followed the same pattern of feedstock mass and BD change – there was no effect of treatment.

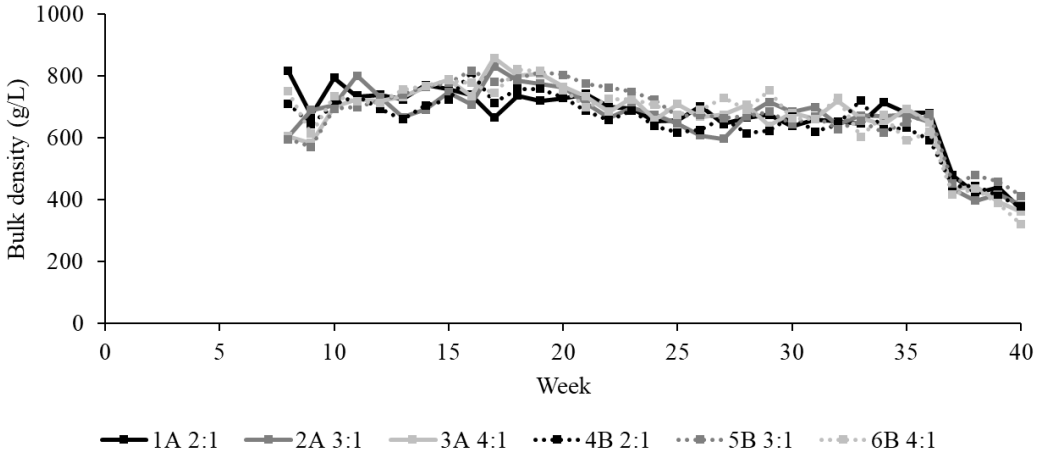


Figure 3-17: Main trial weekly bulk densities. Tub labels and ratio of cardboard to DAF sludge are given in the figure legend.

Feedstock temperatures were measured in the morning each week prior to monitoring and watering (Figure 3-18). Unlike the ambient temperature data (Figure 3-19), these measurements did not give an indication of the variation in feedstock temperature. Except for Weeks 9 and 20, feedstock temperatures were recorded between 15 and 25°C.

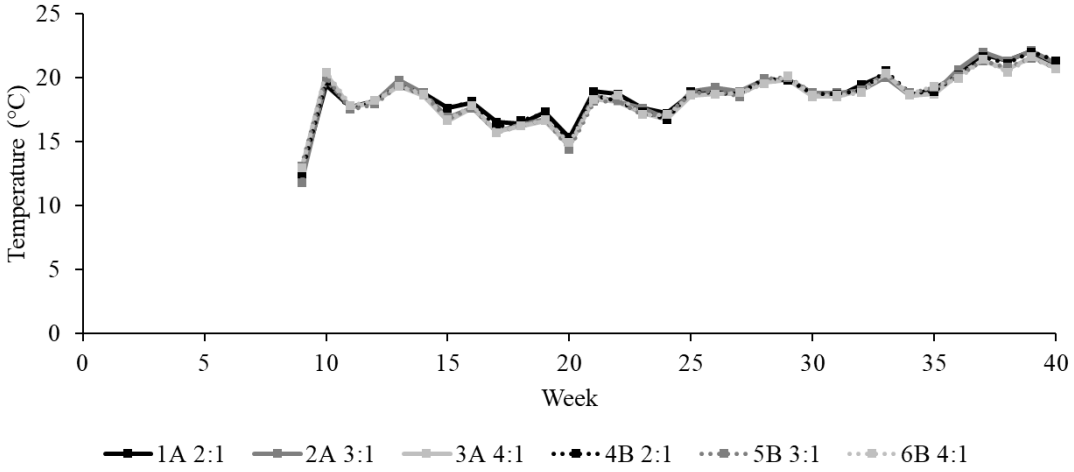


Figure 3-18: Feedstock temperatures taken weekly in the morning (approximately 9:30 am) prior to watering.

In Week 9, a heater was used to minimise exposure of the trial to sub-optimal temperatures and attempt to maintain ambient temperature between 15-25°C. In Week 21, the entire trial was moved to another room and temperature was controlled with a heater on a thermostat set to maintain ambient temperature around 20°C. Ambient temperature data are presented in Figure 3-19.

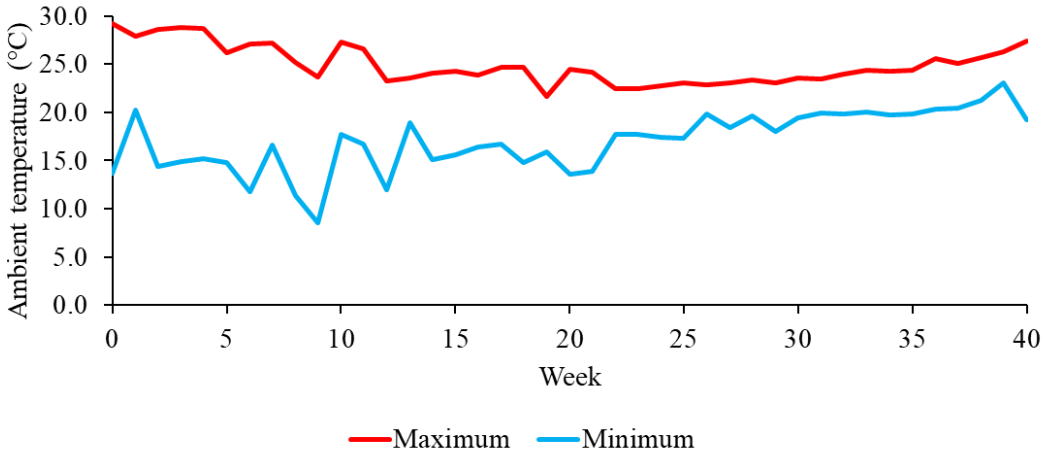


Figure 3-19: Weekly minimum and maximum ambient temperatures for the main vermicomposting trial.

The following results (pH, EC and NH_3) are from the 10 g FM subsamples extracted weekly. The pH results for the feedstocks (Figure 3-20) showed that the initial feedstock pHs were just below 6 and that from Week 7 to Week 14, two distinct trends were recorded. In the seven-week period after the initial inoculation test (survivability of five worms), the pH of Tubs 1A, 2A and 4B (both 2:1 and one 3:1 treatment) were higher than 3A, 5B and 6B (both 4:1 and one 3:1 treatment). The pHs of Tubs 1A, 2A and 4B declined over the seven-week period, while the pHs of Tubs 3A, 5B and 6B remained relatively stable/slowly increased. From Week 15 to Week 35 (mixing of the feedstock), the average trial pH was 6.6. After mixing in Week 36, there was an overall decline in pH in all treatments by the end of the trial.

Tub 4B's pH dropped noticeably after Week 27 (the time when the inoculation sock was removed).

Initially, the ECs in Week 0 were distinctly different between treatments (2:1 at 2.2 dS/m, 3:1 at 1.5 dS/m and 4:1 and 1.3 dS/m). The EC results reflected a similar trend to the pH results in Weeks 7 to 17 where two distinct trends were recorded (Figure 3-21). In the seven-week period after the initial inoculation attempts, the EC of Tubs 1A, 2A and 4B (both 2:1 and one 3:1 treatment) were higher than 3A, 5B and 6B (both 4:1 and one 3:1 treatment). The ECs of Tubs 1A, 2A and 4B declined over the seven-week period, while the ECs of Tubs 3A, 5B and 6B remained relatively stable, but slowly increased.

This steady increase continued to the end of the trial, through the weeks of reduced watering (Weeks 18 to 35), but increasing faster after Week 36 when the feedstock was mixed, with the 4:1 treatments (3A and 6B) having the highest ECs.

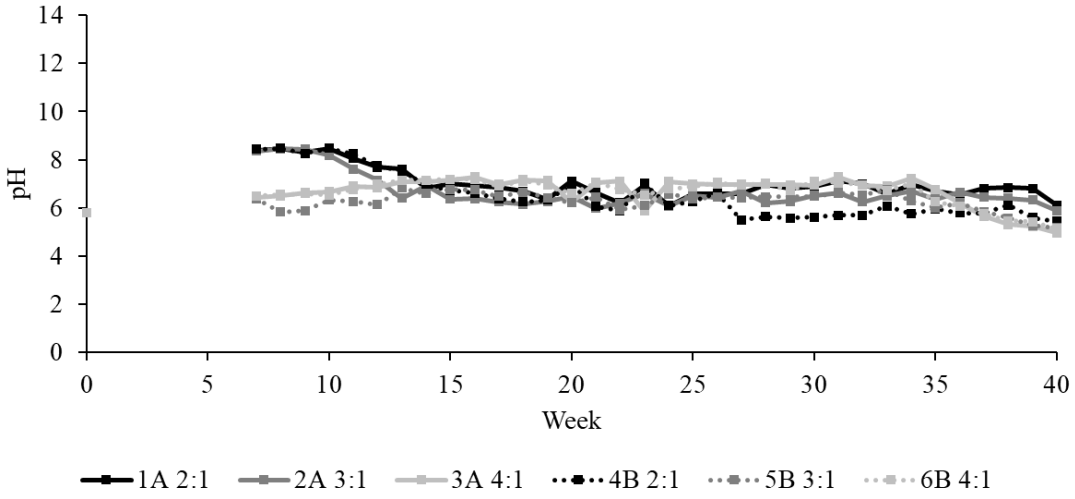


Figure 3-20: Weekly pHs of feedstocks throughout trial. Initial pHs are reported at Week 0 (see Figure 3-14). Tub labels and ratio of cardboard to DAF sludge are given in the figure legend.

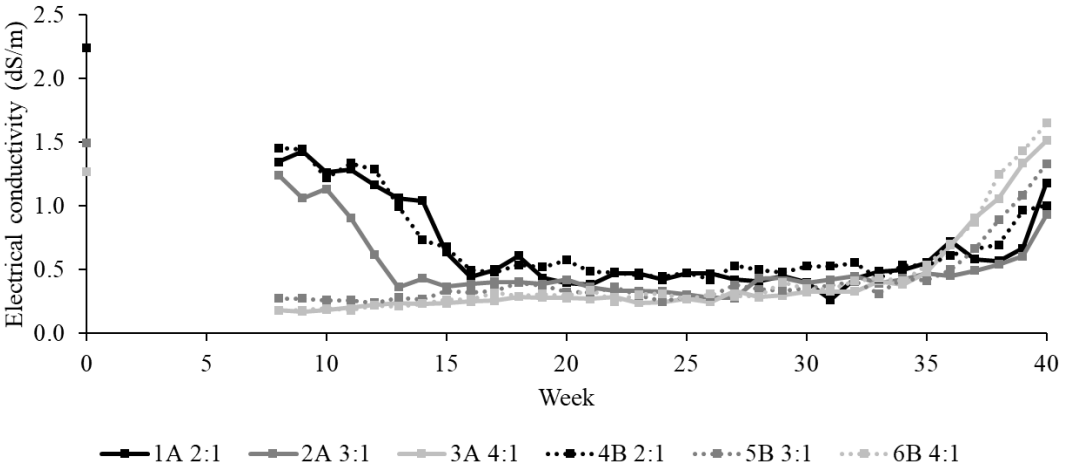


Figure 3-21: Weekly electrical conductivities (EC) of feedstocks throughout trial. Initial ECs are reported at Week 0 (see Figure 3-14). Tub labels and ratio of cardboard to DAF sludge are given in the figure legend.

Ammonia content (measured on the weekly extractant) indicated that NH_3 content of Tubs 1A, 2A and 4B (both 2:1 and one 3:1 treatment) were higher than 3A, 5B and 6B (both 4:1 and one 3:1 treatment). This trend remained relatively stable until Week 19 (watering was first reduced significantly in Week 18). From Week 19 onwards, the NH_3 content of Tubs 1A and 2A dropped. From Week 30 onwards, NH_3 was not detected in any of Tubs 2A, 3A, 5B or 6B. There was the occasional regular spike in NH_3 in Tub 1A, and one in Tub 4B until Week 36 (when mixing occurred), after which NH_3 was no longer detected in any treatment.

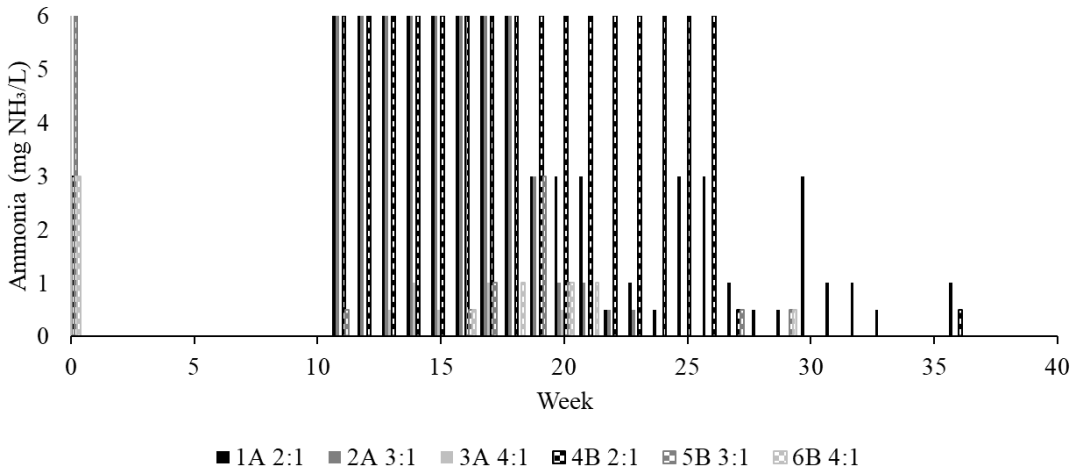


Figure 3-22: Weekly ammonia (NH_3) content of weekly feedstock extractant. Note this is not a direct measure of feedstock NH_3. Tub labels and ratio of cardboard to DAF sludge are given in the figure legend.

3.3.2.5 Other observations

Visual observations were made weekly throughout the trial, mostly regarding presence of moulds and macrofauna. Mould species were not identified. Within one week, moulds were starting to cover exposed pieces of cardboard with more mould visible in the 4:1 replicates. From Week 2 to Week 4, the replicates from each treatment presented similar mould colonies and mites were noted in all treatments from Week 4. Despite the netting, fungus gnats were first noted in Tub 4B in Week 4 and had all treatments by Week 9. Spore densities on the underside of the netting were similar between replicates of each treatment, with the 2:1 presenting the least spores and 4:1 the most. From Week 5, moulds were less visible, but the numbers of mites observed in the tubs were similar between replicates. From Week 6, mould was only visible on pieces of cardboard adhered to the sides of the tubs. From Week 7, the texture of the feedstocks started to differentiate, with the 4:1 replicates tending to have a chunky, aerated texture and the 2:1 replicates a sludgier appearance. Nets covering the tubs were also removed. In Week 19, predatory fungus gnats were observed. By Week 22 their larvae were present in all tubs except 3A.

Upon mixing in Week 36, Tub 1A was noted to have a lot of unprocessed cardboard in the vermicompost and was difficult to homogenise. Tub 2A had a few anoxic zones, characterised by black colour, at the base of the tub and was also difficult to homogenise. Tub 3A had a very friable vermicompost that was easy to homogenise. Tub 4B was difficult to homogenise, with some anoxic spots at the bottom of the tub. Tub 5B was more friable than Tubs 1A, 2A and 4B, but less friable than 3A and 6B, with some cardboard still unprocessed. Tub 6B was friable and easy to homogenise.

	Tub 4B 2:1 Cardboard:DAF	Tub 5B 3:1 Cardboard:DAF	Tub 6B 4:1 Cardboard:DAF	
Feedstock Week 0	A 	B 	C 	P 
Vermicompost Week 40	D 	E 	F 	Q 

	Tub 4B 2:1 Cardboard:DAF	Tub 5B 3:1 Cardboard:DAF	Tub 6B 4:1 Cardboard:DAF	
E. fetida Week 40	G 	H 	I 	R 
Foreign material contamination Week 40	J 	K 	L 	S 

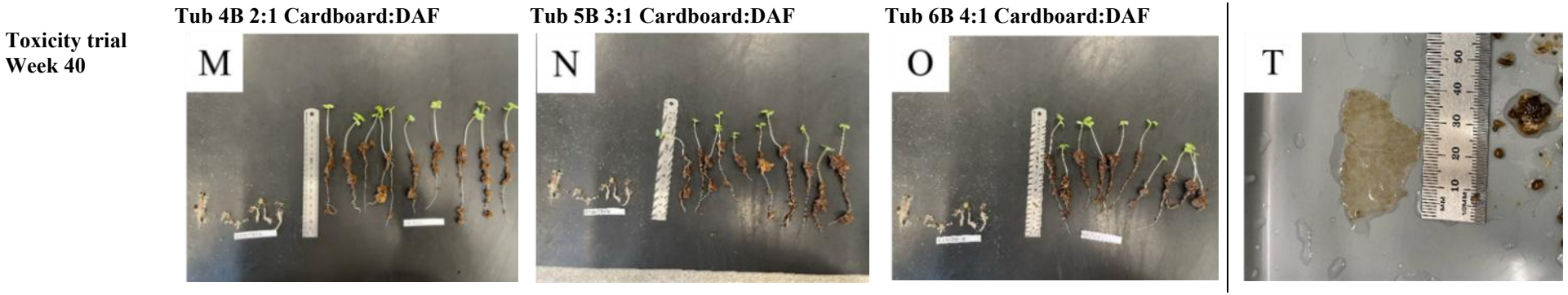


Figure 3-23 A-T. Figure layout has been formatted to compare key features of the main vermicomposting trial and results. The first column of pictures displays Tub 4B, a 2:1 cardboard to Dissolved Air Flotation (DAF) sludge feedstock. The second column of pictures displays Tub 5B, a 3:1 cardboard to DAF sludge feedstock. Tub 6B, a 4:1 cardboard to DAF sludge feedstock. A-C = mixed feedstock at trial initiation (Week 0). D-F = vermicomposts at the trial conclusion (Week 40). G-I = total voided worm (*Eisenia fetida*) biomass recovered at the trial conclusion (Week 40). J-L = foreign material contamination after drying and sieving to 4.76 mm. In each picture, the plastic film is in the rectangular foil tray with the blue tweezers, the oversize vermicast/unprocessed cardboard is in the sieve tray (top right in J, bottom right in K and L) and the vermicast/vermicompost is in the sieve base (bottom right in J, top right in K and L). M-O = radish seedlings grown in pure vermicompost (on right of 150 mm ruler) compared to Control radish seedlings grown in pure Dalton sand (on left of 150 mm ruler). P = trial set up with netting on tubs at Week 0. Q = unprocessed cardboard with plastic film lining adhered (film is between thumb and forefinger, the rest of the material is cardboard with the lining still adhered, refer to pictures S and T also). R = *E. fetida* inhabiting cardboard:DAF feedstock. S = plastic film lining, cocoons and unprocessed feedstock found in Tub 4B during large particle contamination test. T = close up of plastic film lining from Tub 4B during large particle contamination test.

3.3.3 Testing final products against NZS 4454:2005

The following results section follows the structure of Table 3.1 of the New Zealand Standards for composts, soil conditioners and mulches (Standards New Zealand, 2005). From here on, these are referred to as 'the Standards'. The structure reports characteristics in the following order: physical requirements, chemical requirements, biological requirements, microbiological requirements and finally contaminants. Raw data for initial feedstock pH and EC, worm biomass, and radish root length are reported in Appendix 1: main vermicomposting trial raw data.

3.3.3.1 Physical requirements

This section reports particle size grading, ash/volatile solids content, large particle contamination, and bulk density.

The Standard defines a product produced by composting worms as vermicast if >90% of the material passes through a 1.18 mm sieve. If ≤90% than this passes through the sieve, the product is considered a vermicompost. This method does not distinguish what the particles passing though the sieve are, it is just based on size differentiation. Tubs 1A, 2A and 4B (both 2:1 and one 3:1 treatment) had less vermicast (average 7.6%) than 3A, 5B and 6B (average 28.0% vermicast, both 4:1 and one 3:1 treatment). The White Gold product had the highest vermicast content (47.1%). All finished products tested in this study were classed as vermicomposts, not vermicasts (Table 3-18). See photos D-F in Figure 3-23.

Table 3-18: Physical requirement results. Particle size grading results for main vermicomposting trial treatments and industrially produced vermicompost used in the plant production trials (Chapter 4 and Chapter 5). Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks. The minimum required by the Standards is italicised. **Emboldened** results failed the test.

Treatment	Initial mass (g)	>1.18 mm (g)	<1.18 mm (g)	Vermicast	Ash	Volatile solids
Minimum				*≥90%*		
1A 2:1	65.87	59.60	6.27	**10%**	18.0%	82.0%
2A 3:1	61.12	56.71	4.41	**7%**	15.7%	84.3%
3A 4:1	72.53	50.24	22.29	**31%**	12.5%	87.5%
4B 2:1	75.73	71.22	4.51	**6%**	15.6%	84.4%
5B 3:1	65.16	51.32	13.84	**21%**	14.5%	85.5%
6B 4:1	72.36	49.11	23.25	**32%**	12.6%	87.4%
White Gold	172.65	91.39	81.26	**47%**	77.7%	22.3%

While ash/volatile solids contents are not required by the Standards, they were tested. The trial vermicomposts show a low ash content (<25%), high volatile solids

(>75%) content indicating they were dominated by organic material. The industrially produced White Gold vermicompost had high ash (>75%) and low volatile solids (<25%) indicating a lower organic matter content than the trial vermicomposts.

The method for large particle contamination is used to determine whether a finished product is sufficiently uncontaminated with large particles to be classed as a vermicompost. The results are reported in Table 3-19, along with bulk density measurements. See photos S and T in Figure 3-23 for an example of the contamination. A threshold of 10% is reported by the Standards for large particle contamination i.e. 90% or more of the finished product must pass through a 1.18 mm sieve when saturated. Tubs 1A and 2A failed this test (11 and 13% of particles were greater than 1.18 mm in this test).

A slightly lower volume of White Gold was tested than the trial vermicomposts due to the vermicompost compacting when fully saturated. The White Gold was slower to drain through the 25x 2.5 mm holes in the base of the measuring beaker than the trial vermicomposts immediately after saturation and prior to wet sieving. However, the White Gold was noticeably faster to wash through the sieve than the trial vermicomposts and had a 'siltier' texture than the trial vermicomposts.

Due to low volumes of vermicompost available for testing, an alternative method of measuring bulk density (BD) was employed. The bulk density averaged 0.52 g/L across the trial vermicomposts and was higher (0.82 g/L) in the industrially produced White Gold vermicompost. There were no recommended densities in the Standards.

Table 3-19: Large (>1.18 mm) particle contamination and bulk density results for trial and White Gold vermicomposts. BD = bulk density. Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks. The minimum required by the Standards is italicised. Emboldened results failed the test.

Treatment	**Volume tested**	**Particles >1.18 mm**		**Sample mass**	**Sample volume**	**BD**
	mL	**mL**	**%**	**g**	**mL**	**g/L**
Minimum			*<10%*			
1A 2:1	500	55	**11%**	437.71	900	0.49
2A 3:1	500	65	**13%**	403.36	800	0.50
3A 4:1	500	30	6%	454.43	850	0.53
4B 2:1	500	35	7%	432.12	850	0.51
5B 3:1	500	25	5%	464.89	850	0.55
6B 4:1	500	30	6%	489.82	950	0.52
White Gold	450	20	4%	741.79	900	0.82

3.3.3.2 Chemical requirements

This section reports pH, electrical conductivity (EC), soluble nutrients, total nutrients, C:N, organic matter content, heavy metals, and moisture content. Note that

organic contaminants were not tested, as explained in Table 3-6. The following results are reported in Table 3-20.

Under the Standard, the allowed pH range of vermicasts, soil conditioners and vermicomposts is 5.0 – 8.5. Of the trial vermicomposts, Tubs 1A, 2A and 4B had the highest pHs (6.05, 5.74 and 5.48, respectively) and lowest ECs (1.8, 1.4 and 1.7 dS/cm, respectively). Tub 3A (a 4:1 treatment) had a pH of 4.89 (failing the Standards), while Tub 6B (another 4:1 treatment) had a pH of 5.02 and 5b (a 3:1 treatment) had a pH of 5.08. Correspondingly, these treatments also had the highest ECs, though these were not above the limits of the Standards (2.5 dS/m maximum).

The White Gold vermicompost had the most neutral pH (7.08) and a relatively high EC (2.5), but just within the Standards limits.

Table 3-20: Chemical requirement results. pH, electrical conductivity (EC), soluble phosphorus (sol. P), ammonium and nitrate nitrogen (NH_4^+-N and NO_3-N), total C and N, carbon nitrogen ratio (C:N), organic matter (OM) and boron (B) contents. Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks. Note that boron *(italicised)* was detected below quantitation limits, ND = not detected. The minimum required by the Standards is italicised. Emboldened results failed the test. See below for results reported in grey text.

Treatment	**pH**	**EC**	**Sol. P**	**Total P**	**NH_4^+-N NO_3^-N**	**Total C**	**Total N**	**C:N**	**OM**	**B**
		dS/m	**mg/L**	**%DM**	**mg/L**	**% DM**	**% DM**		**%**	**mg/kg DM**
Minimum	*5.0-8.5*	-				-	*≥0.6*		*≥25*	*<200*
1A 2:1	6.05	1.8	25.86	2.00	52.36	46.90	2.63	17.8	71.8	*103*
2A 3:1	5.74	1.4	22.15	1.83	34.86	48.59	2.65	18.3	74.3	*112*
3A 4:1	4.89	2.5	18.01	1.30	97.11	50.45	3.15	16.0	77.2	*102*
4B 2:1	5.48	1.7	*	1.99	35.11†	47.63	2.53	18.8	72.9	*88*
5B 3:1	5.08	2.4	*	1.93	*	49.11	2.93	16.8	75.1	*80*
6B 4:1	5.02	2.3	20.64	1.31	163.18	50.10	3.11	16.1	76.7	*97*
White Gold	7.08	2.5	‡	0.38	149.59	14.6	0.82	17.7	25.2	ND

White Gold Total C, Total N, C:N and OM contents are from an independent test on a similar batch of vermicast tested in 2021 and are reported here as estimates only (grey text).
*not enough sample for testing
†NO_3^- tested and reported, but not NH_4^+
‡reported result was negative

Total P decreased with cardboard content which was expected given the DAF sludge supplied the P nutrients. There is no limit for total or soluble P (except in cases where a product is marketed for P-sensitive plants, in which case, limits of ≤5 mg/L soluble P and ≤0.1% DM for Total P are stated). No vermicompost tested was suitable for P-sensitive plants. The Total N and P contents of the White Gold vermicompost were much lower than the trial vermicomposts. As well as being produced from a different feedstock (milk processing waste activated and DAF sludges, and pulp and paper mill solids), the White Gold vermicompost was produced in an outdoor environment. The

weather conditions it would have been subjected to would likely have resulted in losses of nutrients via leaching. However, it was noted in a preliminary test that the White Gold vermicompost readily released water soluble P, indicating its value for plant nutrient supply (results not reported).

Soluble N must be >10 mg/L if the product is claimed to contribute to plant nutrition. All treatments therefore supplied sufficient plant available N, though 5B was unable to be tested due to low sample volume. Tub 4B was only tested for NO_3^- as there was not enough sample for NH_4^+.

Total N, Total C and correspondingly organic matter content (OM) increased with cardboard content, however, C:N varied between treatments. The C/N ratios were higher in Tubs 1A, 2A and 4B (averaging 18.3) and lower in Tubs 3A, 5B and 6B (averaging 16.3). For all trial vermicomposts, N content was >0.6% DM. The Standards state that N content must be greater than this if a contribution to plant nutrition is claimed. All OM contents were >25% DM (calculated as 1.7 x C%), which is the minimum requirement for the Standards. Although they were below quantitation limits, all B results were below the 200 mg/kg DM threshold specified in the Standards. Boron was present in all trial vermicomposts. It was not detected in the White Gold vermicompost, however an independent test report (results not reported here) did indicate B could be present in this vermicompost although well below the 200 mg/kg DM threshold for the Standards.

Heavy metal concentrations were compared to the 2003 Guidelines for the safe application of biosolids to land in New Zealand, as referred to in the 2005 New Zealand Standards for Composts, soil conditioners and mulches (New Zealand Water and Wastes Association, 2003; Standards New Zealand, 2005). As the biosolids guidelines have been updated since the 2003 version and the Standards, these (higher) limits have also been included in

Table 3-22. None of the limits for other heavy metals were approached or exceeded by the vermicomposts.

All trial vermicomposts tended to have higher heavy metal contents than the initial feedstocks due to concentration via volume reduction. When averaged between the two replicates for each feedstock ratio, Zn was concentrated in the vermicomposts the most (54.2, 57.4 and 45.2-fold increases for 2:1, 3:1 and 4:1 treatments, respectively), followed by K (7.6, 14.9 and 12.5-fold increases for 2:1, 3:1 and 4:1 treatments, respectively). All other nutrients, except N, increased approximately 5.5-fold on average. Nitrogen increased 1.2, 1.6 and 2.0-fold increases for 2:1, 3:1 and 4:1 treatments, respectively. No

limits were provided by the Standards for major and minor plant nutrients, except for a note that Mg and Ca are to be reported when Na content is ≥1%, which it was in all tubs.

Moisture contents were acceptable for all vermicomposts – the threshold for the Standards is 25% moisture content (Table 3-23).

Table 3-21: Major and minor plant nutrients detected in trial vermicomposts. Results reported in mg/kg DM. *Italicised* results are below quantitation limits. ND = not detected. Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks.

Treatment	**1A 2:1**	**2A 3:1**	**3A 4:1**	**4B 2:1**	**5B 3:1**	**6B 4:1**
Major plant nutrients						
N	20,037	18,309	12,966	19,895	19,299	13,131
P	1,816	1,643	1,306	1,883	1,857	1,226
K	*6,570*	*6,484*	*6,244*	*6,536*	*6,820*	*5,893*
S	*13,726*	*10,830*	*8,945*	*9,496*	*9,449*	*9,503*
Ca	1,742	1,615	1,301	1,713	1,654	1,337
Mg	20,037	18,309	12,966	19,895	19,299	13,131
Minor plant nutrients						
Al	15,185	14,066	10,695	14,748	14,164	11,115
B	*103*	*112*	*102*	*88*	*80*	*97*
Co	*0.99*	*0.89*	*0.91*	*0.94*	*0.79*	*0.78*
Fe	1,692	1,547	1,309	1,518	1,457	1,330
Na	3,696	3,592	3,515	3,635	3,474	3,565
Mn	110	106	90	110	105	95

Table 3-22: Heavy metal contents detected in trial vermicomposts, compared to the limits for land application of biosolids in New Zealand (New Zealand Water and Wastes Association, 2003; Water New Zealand, 2025). Results reported in mg/kg DM. ND = not detected. *Italicised* results are below quantitation limits. Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks.

Heavy metal	**1A 2:1**	**2A 3:1**	**3A 4:1**	**4B 2:1**	**5B 3:1**	**6B 4:1**	**2003 limit**	**2025 limit**
As	*2.43*	*1.80*	*1.87*	*2.37*	*2.05*	*1.49*	20	30
Cd	*0.09*	*0.09*	*0.22*	*0.21*	*0.13*	*0.12*	3	6.5
Cr	17	10.1	7.60	8.51	7.51	7.91	600	1,500
Cu	515	48	39	50	49	39	300	750
Pb	3.92	3.60	3.70	3.19	3.02	3.60	250	300
Hg	ND	ND	ND	ND	ND	ND	2	7.5
Ni	6.00	5.20	4.12	5.41	5.17	4.19	60	135
Zn	266	247	186	266	259	185	600	1,250

Table 3-23: Moisture contents of trial and White Gold vermicomposts. Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks. The minimum required by the Standards is italicised. Emboldened results failed the test.

Treatment	DM%	MC%
Minimum		*>25%*
1A 2:1	24.1%	75.9%
2A 3:1	23.4%	76.6%
3A 4:1	25.8%	74.2%
4B 2:1	24.4%	75.6%
5B 3:1	23.4%	76.6%
6B 4:1	25.3%	74.7%
White Gold	47.9%	52.1%

3.3.3.3 Biological requirements

This section reports toxicity, plant propagules (weed contamination), and plant growth index. Note that no method for "biology" was provided so this was not tested (Table 3-6).

For the toxicity trial, moistening of products was not required as moisture contents were all >40%. Electrical conductivity of all products was ≤2.5 dS/m therefore the leaching method was not required and the standards method described in the Standards was used. The same cultivar of radish (Long Scarlet) required for the test was not available. Instead, French Breakfast was used. Average root length is reported in Figure 3-24. All treatments, regardless of application method performed better than the control and exceeded the 20 mm threshold for toxicity. The most beneficial treatment was the pure vermicompost. White Gold grew the greatest average root length (102 mm). The least beneficial treatment was the incorporated treatment, though this still outperformed the Control.

The application method made a difference to root length – see Figure 3-24 (raw data provided in Table 8-3). This was confirmed by ANOVA (Table 3-24). Pure vermicompost was the most effective at promoting root growth. Although root lengths appeared longer where vermicompost broadcast (surface applied) over sand had longer roots than the same rate (12.5 t FM/ha) mixed into sand, this difference was not significant.

Although not required by the method, moisture content of the treatments at the end of the experiment was measured. The Dalton sand Control was 6.8%, which was similar to the trial and White Gold broadcast and incorporated treatments (6.2%, range 5.5-7.3%). The pure vermicomposts averaged 77.2% moisture (range 74.7-78.7%) while the White Gold was 53.7%. All are similar to the results reported in Figure 3-24, indicating moisture contents were maintained throughout the trial.

Table 3-24: Average radish seedling root length for different vermicompost application methods. The data are from the toxicity test. SD = standard deviation. Letters a and b denote significant differences between application methods. Broadcast = surface applied.

Application method	Average root length ± SD (mm)
Incorporated	32.7 ± 6.8 a
Broadcast	41.1 ± 3.7 a
Pure	92.3 ± 7.4 b
ANOVA p value	$8.25x10^{-13}$
Levene's test p value	*0.4034*

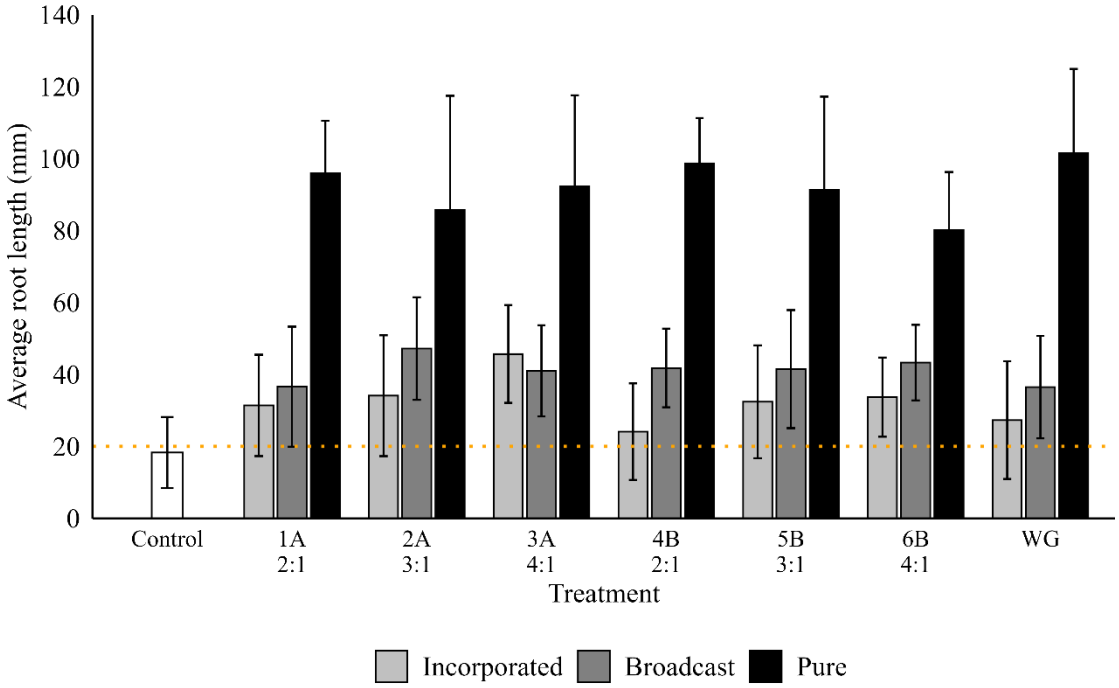


Figure 3-24: Average radish seedling root length for toxicity test. Error bars are standard deviation of 10 seedlings per replicate (one replicate per treatment, n = 1). Orange dotted line indicates the minimum root length required to determine a vermicompost is non-toxic. Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks.

No plant propagules were detected in the vermicomposting trial vermicomposts. All vermicomposts passed this test indicating that the inputs and processes followed did not introduce plant propagule or weed seed contamination.

Although plant growth index (PGI) was not a test required for vermicomposts under the Standards, a test was conducted. A PGI ≥2 indicates the product supports plant growth. The results showed that all methods of vermicompost application increased plant growth by an index of at least two or more. The pure vermicompost was the most beneficial for plant growth, followed by the 1:1 mixes and finally treatments broadcast at 12.5 t FM/ha. In the 1:1 treatments, the White Gold vermicompost performed poorly

compared to the trial vermicomposts, though it performed as good as if not better than the trial vermicasts when broadcast at 12.5 t FM/ha (Table 3-25).

No tests for biology were done as no method was recommended in the Standards ("the biology of compost is vitally important for the release of nutrients contained within the compost. Development of a methodology to determine how this is to be measured is subject to further work" (Standards New Zealand, 2005)).

Table 3-25: Average masses of tomato plants grown with vermicompost as a 1:1 mix or broadcast (surface applied). Plant growth index (PGI) of tomato plants grown against a pure sand control.

Treatment	Mixture	Average mass (g)	Replicates	PGI
Control	Pure sand	0.37	3	1
1A	Broadcast 12.5 t FM/ha	0.85	3	2
2A	Broadcast 12.5 t FM/ha	0.85	3	2
3A	Broadcast 12.5 t FM/ha	1.76	3	5
4B	Broadcast 12.5 t FM/ha	0.71	3	2
5B	Broadcast 12.5 t FM/ha	1.06	3	3
6B	Broadcast 12.5 t FM/ha	1.07	3	3
WG	Broadcast 12.5 t FM/ha	1.92	3	5
1A	1:1 vermicompost:sand	26.01	1	70
2A	1:1 vermicompost:sand	33.52	1	91
3A	1:1 vermicompost:sand	62.80	1	170
4B	1:1 vermicompost:sand	27.63	1	75
5B	1:1 vermicompost:sand	36.23	1	98
6B	1:1 vermicompost:sand	28.99	1	78
WG	1:1 vermicompost:sand	2.43	3	7
Vermicompost	Pure vermicompost[†]	113.31	1	306

[†]The pure vermicompost mix was made up of the remnants of all trial vermicomposts after all tests, excluding 6B and White Gold.

3.3.3.4 Microbiological requirements

This section reports microbiological testing.

The Standards state samples for microbiological testing must be received within six hours of collection and analysed immediately. Initially, the samples submitted for *Escherichia coli* testing were tested as sludges as the independent lab reported that "the sample was too thick to pipette out and was diluted 100-fold". The reported initial results (all <180 MPN/100 mL) were not comparable to the Standard (limit of <100 MPN/g) so the samples were retested following a more suitable method for comparing to the Standards. This meant the results were reported 7 days after sampling – a time delay of nearly a week which did not meet the requirements of the Standards. However, the final reported results were <2 MPN/g i.e. less than the default detection limit of 2 MPN/g. Despite the time delay in testing, these results were believable as the DAF sludge came from the food grade processing plant and the paper was cardboard – there should not have been any *E. coli* (faecal contamination indicator) in either input.

3.3.3.5 Contaminants

This section reports foreign material contamination.

The thresholds for foreign material contamination >5 mm are: ≤0.4% DM for glass, metal and rigid plastics, ≤5% DM for stones and lumps of clay and ≤0.04% for light, flexible or film plastics. No test samples contained glass, metal or rigid plastics. The trial vermicomposts did not meet the Standards for plastic films, as there was significant contamination in all tubs (Table 3-26, see photos D-F and J-L in Figure 3-23). This was from the cardboard trialled. There was some difficulty in separating the plastic film from the dried vermicompost which may have influenced results slightly (see photos Q, S and T in Figure 3-23). However, the plastic contamination was very obvious in the final product. The White Gold vermicompost did not contain plastic films, however it did contain stones and clay clod (0.5% DM), but well below the contamination threshold. It should be taken into consideration that the White Gold vermicompost had been screened to 2 mm prior to its use in all trials. This would have affected the quantity of foreign material removed.

Table 3-26: Foreign material contamination of vermciomposts. Treatment labels indicate the tub and cardboard to dissolved air flotation (DAF) sludge ratio of the feedstocks. The minimum required by the Standards is italicised. Emboldened results failed the test.

Treatment	Total sample g DM	Plastic >5 mm g DM	Stones and clay g DM	Plastic %DM w/w	Stones and clay %DM w/w
Minium				*≤0.04%*	*≤5%*
1A 2:1	55.17	1.54	-	**2.8%**	0.0%
2A 3:1	48.32	1.78	-	**3.7%**	0.0%
3A 4:1	60.13	1.62	-	**2.7%**	0.0%
4B 2:1	56.98	0.96	-	**1.7%**	0.0%
5B 3:1	54.27	0.96	-	**1.8%**	0.0%
6B 4:1	65.08	1.41	-	**2.2%**	0.0%
White Gold	181.98	-	0.92	0.0%	0.5%

3.4 Discussion

3.4.1 Pilot trial

3.4.1.1 Suitability of feedstocks for vermicomposting

Pure DAF sludge was toxic to worms throughout the trial. The failure of the pure DAF treatments to support *E. fetida* at any stage of the experiment, even five and a half months after the trial began, indicated that the sludge alone was unsuitable for vermicomposting under the tested conditions. The inability of the pure DAF sludge to support *E. fetida* in the pilot trial precluded its inclusion as a treatment in the main trial. The suitability of sludges for vermicomposting depends on their origins and characteristics. Other vermicomposting studies tend to blend sludges with a carbon source though other studies e.g. Dume *et al.* (2023) and Hleibieh *et al.* (2026) have shown compost worms to successfully vermicompost both pure and co-composted sewage and aquaculture sludges.

Interestingly, the accidental contamination of one of the pure DAF treatments with fly maggots (that successfully reached the adult stage of their life cycle) indicated that pure DAF sludge may be more appropriate for insect farming such as black soldier fly larvae (BSFL). However, the only study currently available on the topic of BSFL processing of chicken DAF sludge showed that processing of pure DAF was inferior to all other feedstocks (different mixtures of DAF:foodwaste from 1:0 to 0:1). It also showed that pure DAF's performance e.g. biomass gain of 1.2 mg/larva/day was well below the "gold standard" of BSFL raised on poultry feed i.e. 9 mg/larva/day (Shanmugam *et al.*, 2025).

The composting treatments (no worms) did not completely process by the time the experiment concluded as pieces of undecomposed cardboard were present in all compost replicates (compare Figure 3-12 (vermicomposted) to Figure 3-13 (composted)). The Cardboard:DAF feedstocks therefore processed faster when worms were present, except for the pure DAF sludge. By the end of the trial, both the compost and vermicompost had similar elemental make up. The ash content of the composted treatments was lower than their respective vermicasts, but not significantly so. The DAF had the highest ash content, indicating a higher mineral and lower organic matter content.

The pilot trial used the same quantity (50 g DM feedstock) and stocking rate (five non-clitellated *E. andrei*/50 g DM*)* as Fernández-Gómez *et al.* (2010) who studied the feasibility of vermicomposting greenhouse wastes with *E. andrei*. Fernández-Gómez *et al.* (2010) reported their initial inoculation of feedstocks containing heterogenous-plant

or tomato-plant wastes failed within 24 hours and attributed this to the high EC content of these wastes (17 ± 0.10 and 12.0 ± 0.01 dS/m, respectively). However, compared to the other wastes trialed in their study, C:N appeared low for both feedstocks (7 ± 0.2 and 9 ± 0.1 respectively) and this may have contributed to mortality (see Section 3.4.2.2 regarding sour crop). In another trial by Gunadi and Edwards (2003), young pig solids with a C:N of 9.3 ± 0.4 and EC of 8.2 ± 0.7 dS/m were used as a feedstock for *E. fetida*. As well as a low C:N and high EC, this feedstock had a high NO_3^- content (9,803.2 ± 605.9 mg/kg). However, the NH_4^+ content of young pig solids (44.0 ± 4.5 mg/kg) did not appear to be a contributing factor to earthworm mortality as there were other successful feedstocks with higher NH_4^+ contents e.g. sow pig solids (1,424.9 ± 55.2 mg/kg). The sow pig solids feedstock also incidentally had one of the highest growth rates in the first three months (7.8 ± 0.5 mg [per worm]/day) and the lowest mortality rate in the study after 23 weeks (22%). These results demonstrate that earthworm tolerance and suitablity of feedstocks for vermicomposting depend on multiple factors.

The pilot trial pH was similar between the pilot feedstocks (averaging 5.8). Electrical conductivity was highest in the pure DAF sludge (3.6 dS/m) and decreased with increasing cardboard content. A more concentrated extraction method was used in the main trial (1:5 w/v) compared to Fernández-Gómez *et al.* (2010) who used a 1:10 w/v extraction. The pilot trial DAF sludge had a much lower EC than the failed treatments reported by Fernández-Gómez *et al.* (2010) and may not have been the cause of the DAF's unsuitability for vermicomposting. Other factors such as additives used to coagulate or flocculate solids in the DAF processing plant or at other stages of wastewater treatment could also impact worm health.

3.4.1.2 Potential issues with heavy metals

It appears both the DAF sludge and the cardboard were sources of Cadmium. Cadmium was detected below quantitation limits, so the results reported should be interpreted with caution. The results show that the concentration of Cd increased over the trial period as the volume of material reduced and that Cd may have exceeded both the 2003 and 2005 limits in both the inputs for the feedstock and the finished composts/vermicomposts. Retesting at a lower dilution factor would be required to confirm this result, but this was not possible due to the small amount of vermicompost available for testing. Cadmium is a potential contaminant from poultry farming. Bolan *et al.* (2010) reported that heavy metal concentrations (e.g. Cd) are a limiting factor for

repeated applications of chicken litter given their persistence in soils and health consequences, although apparently this is not an issue in New Zealand (Kerry Mulqueen, personal communication, November 11, 2022). Cadmium ends up in poultry by-products such as chicken litter and DAF sludge through the feed (Bolan *et al.*, 2010). It is also present in paper products such as cardboard and inks, however not always at concerning levels (Mertoğlu-Elmas & Çınar, 2018). If upon retesting, Cd was found to exceed the limits for land application, a different source of cardboard/paper waste with a lower Cd content may be able to be used to dilute the Cd content of the DAF sludge. Alternatively, bioremediation using higher population densities of compost worms may be possible to remove Cd from feedstock material (Hartenstein *et al.*, 1980), however this affects the viability of using *E. fetida* as a protein source e.g. worm meal for aquaculture.

3.4.1.3 *E. fetida* reproduction and biomass production

The final worm biomass for all treatments was higher at the end of the experiment than at inoculation. As the worms were not voided for this measurement, statistical analyses were not performed to determine the significance of the differences, though it is reasonable to assume that all surviving worms gained biomass over the duration of the experiment as gut fill is estimated at 3-5% of liveweight for adult *E. fetida* fed sludge (Hartenstein *et al.*, 1981). Assuming gut fill from feedstocks only accounted for 5% of liveweight at the final weighing, there was an observable increase in adult worm liveweight over the four-month vermicomposting period, most noticeable in the 2:1 Cardboard:DAF treatment, though this was not statistically significant. The higher bioconversion efficiency in the 2:1 treatments also indicated a tendency for the lower cardboard feedstock to promote biomass production.

Gunadi *et al.* (2003) reported higher *E. fetida* biomass and fewer cocoons produced in feedstocks derived from pig manure solids (C:N = 15.3:1) than cattle manure solids (C:N = 41.4:1), and indicated this could be due in part to lower C:N in the pig manure feedstocks. Gunadi and Edwards (2003) also reported higher *E. fetida* biomass and fewer cocoons in feedstocks with lower C:N (32.3-36.4:1 vs 13.2-16.9:1). In the pilot trial, *E. fetida* biomass data were too noisy to detect trends. However, the 2:1 (C:N 26.0) and 3:1 (C:N 36.8) treatments produced fewer capsules than the 4:1 (42.7) treatments although this was not statistically significant due to the high variation between replicates. Initially, the greater number of cocoons in the 4:1 treatments was attributed to the higher C:N as per the previous referenced studies. However, a study by Gupta *et al.* (2007) showed that higher C:N feedstocks benefited both biomass production and reproduction.

Their initial C:N range was 36.0-60.6. In their study, the higher the C:N, the greater the worm biomass, hatchling and cocoon production. However, according to other studies, higher C:N does not necessarily favour reproduction over biomass production, though individual worms may be larger at lower C:N due to N availability. The C:N ranges discussed here vary widely. There do not appear to be clear thresholds for whether a certain feedstock will support or kill compost worms (*Eisenia* genus). When researching available literature, survival and biomass/reproduction data indicate that parameters such as N species, EC, pH and C:N can be outside recommended ranges and *E. fetida* thrive (Gunadi & Edwards, 2003; Gunadi *et al.*, 2003; Gupta *et al.*, 2007) and that for moisture content, the age of the worm dictates its preference (Gunadi *et al.*, 2003). However, Tiunov and Scheu (2004) showed that for an endogeic species (*Octolasion tyrtaeum*), the availability of C was important – total C had less effect than labile C on biomass production.

The feedstocks initially started out at 83.2% DM for pure DAF (moisture content, as received) and 75.6% across all Cardboard:DAF treatments. This was the was the maximum amount of moisture the 4:1 Cardboard:DAF treatments could hold as the cardboard's ability to absorb water was the limiting factor. While the feedstock moisture contents were lower than the optimal moisture content of 80-90% recommended by Edwards (1985), they did support *E. fetida*. In practice, optimal moisture content appears to vary depending on the feedstock (Gunadi *et al.*, 2003) and age of the worms (Reinecke & Venter, 1987).

Biruntha *et al.* (2020), demonstrated that the growth rate of *E. eugeniae* (a close relative of *E. fetida*) was dependent in pH, TOC, TKN and C:N and that their cocoon production was dependent on the same parameters, as well as growth rate. Electrical conductivity (initially 1.49 – 2.09 dS/m in feedstocks) did not have a significant effect on reproduction or growth rate. While not the focus of their study, data reported in Gunadi and Edwards (2003) show that cattle and pig solids from different sources had varying EC contents. In their study, feedstocks with ECs higher than 3.2 dS/m generally tended to result in high or total mortality rates (75-100%), sometimes immediately. Interestingly, their pre-composted cattle solids feedstock had an EC of 3.4 dS/m, and the second lowest mortality rate (28%, behind sow pig solids with an EC of 3.2 dS/m and mortality of 22%.

C:N decreases as vermicomposting/composting proceed e.g. (Gunadi *et al.*, 2003; Gupta *et al.*, 2007; Fernández-Gómez *et al.*, 2010; Gigliotti *et al.*, 2012; Biruntha *et al.*, 2020; Dume *et al.*, 2023). Aira *et al.* (2006) showed that microbial activity decreased over time as C:N declined (with feedstock age). This trend was observed in 19:1 and 11:1 C:N

feedstocks of pig slurry. Their study also showed that substrate induced respiration was enhanced in younger feedstocks and depressed in older feedstocks. Dissolved organic carbon (DOC) was significantly affected by feedstock age, but not affected by C:N.

Biruntha *et al.* (2020) reported significant differences in C:N between compost vs vermicompost produced by *E. eugeniae* C:N. In the pilot trial, samples were pooled so statistical analyses could not be performed, however, there was little discernible difference between composted and vermicomposted final products.

Ash content increased by an average of 72.3% across DAF treatments and 156.1% across all other treatments (Cardboard:DAF final products). Volatile solids (VS; reciprocal of ash), decreased by 20.0% across all pure DAF treatments and 16.2% across all other treatments. This was approximately twice the reduction reported by Ndegwa and Thompson (2000) for feedstocks derived from paper mulch + biosolids fed to *E. fetida* in a 5 week period for treatments with similar C:Ns to the pilot trial. It is likely that the low VS reduction in the pilot trial in the composted/vermicomposted feedstocks was due to the resistance of C to degradation e.g. in the form of lignin and cellulose which were provided by the cardboard (Mboowa, 2024; Vikman *et al.*, 2024).

3.4.1.4 Converted feedstock (final products)

Final DMs between vermicomposted and their counterpart composted treatments were not significantly different, although despite the lack of significance for the Cardboard:DAF feedstocks, when worms were present, on average 2-4% more DM was lost. In comparison, there was a 1% difference in final DM between pure DAF treatments. The differences in Cardboard:DAF treatments are small, but the trend between vermicomposting and composting treatment final DM is consistent. There is low variation in the DM data, especially considering the large variability in worm biomass and population parameters. At least some of this difference could be explained by worm biomass (including gut fill), however, as *E. fetida* DM content is reported as 17.8% (Kostecka *et al.*, 2022), biomass accumulation is unlikely to have contributed more than 1% to the DM loss. Therefore, these factors indicate that there may still be a small but meaningful difference in DM losses when worms are present.

The bioconversion efficiencies (BE) of the vermicomposted treatments were highest in the 2:1 treatments, but given the high variability, they were not largely different from the 3:1 and 4:1 treatments, similar to the adult worm biomass at the end of the trial.

Due to the selected dilution used for ICP-MS analysis, not all nutrients were detected above their respective QLs. However, as trends in the element concentrations

matched the changes in Cardboard:DAF, these values were accepted and reported. For example, in the initial feedstocks, as the concentration of cardboard increased, the concentration of calcium increased. Cardboard is primarily made from carbon with a very low N content, hence its wide C:N. This trial used corrugated cardboard, of which part or all may have been produced by the Kraft process. The Kraft pulping process uses sodium sulphide, which allows the cellulose in virgin wood fibres to retain their strength in the finished material (Mboowa, 2024). Both Ca and S used in the process may be retained, which could be why they are the most and second most common elements in the cardboard behind C.

Total elements increased by the end of the trial, in all feedstocks, including the pure DAF treatments. Vermicomposting enhanced this effect over composting, aligning with results in the literature although the results in the pilot trial were exaggerated compared to Gupta *et al.* (2007) and Dume *et al.* (2023). Regarding N, Ndegwa and Thompson (2000) demonstrated a decrease in TN in their vermicomposting study. In the pilot trial, N content did decrease in the pure DAF treatments, but not the feedstocks mixed with cardboard – the increase in N content was much the same as the other elements, although the higher the cardboard content, the higher the increase in N in the final product.

3.4.1.5 External factors

Ambient temperature fluctuated within a range of nearly 20 °C. The feedstock temperature was not measured, but except when first mixed, and there may have been some heating of the small quantities of feedstock, was likely to have been similar to the ambient temperature and would not have fallen below the minimum recorded temperature of 11.4 °C. Optimal temperature conditions for *E. fetida* are reported to be 25°C, with a tolerance between 0-35°C (Edwards, 1985; Edwards & Neuhauser, 1988). While ambient temperatures varied throughout the trial, they did not exceed either end of *E. fetida*'s tolerance range.

Fungus gnats were found in all treatments, including the pure DAF treatments. Frass from these fungus gnats was not obvious in vermicomposting treatments (compare Figure 3-12 (vermicomposted) to Figure 3-13 (composted)). This may have been due to competition, or frass may have eventually been vermicomposted. However, fewer fungus gnats noticed in the 4:1 treatments (including replicates without worms) could indicate that cardboard was not their preferred food source, which aligns with their presence in the pure DAF treatments.

Monitoring of worm counts and biomass were performed monthly in the pilot trial. It was considered that this may have stressed the worms, slowing the progress of the vermicomposting. However, other studies report weekly monitoring of individual worm biomass over extended periods (>23 weeks) and did not report any ill effects (Gunadi & Edwards, 2003; Gunadi *et al.*, 2003).

Although the vermicomposting was successful, it was difficult to determine statistically significant trends between treatments. The results indicated that all ratios were suitable for vermicomposting, with the 4:1 driving breeding based on higher numbers of capsules and the 2:1 driving biomass gains, although this generalisation was not statistically significant. The 4:1 treatments had the highest and least variable worm survival rates (the least variation and fewer mortalities and replacements). In some months, some 3:1 treatments had few to no worms. While the cause remains inconclusive, it was assumed that worm mortalities were not due to monthly sampling or toxicity of the feedstock, given the 2:1 and 4:1 treatments did not show signs of negative impact due to sampling and did not appear to be toxic, unlike the pure DAF treatments which remained toxic to worms, even five months after starting the trial. The lack of difference between the Cardboard:DAF treatments may have been due to the small sample size and high within-treatment variability i.e. true differences may have been obscured.

3.4.2 Main trial

3.4.2.1 Feedstock characteristics and worm activity

The addition of five worms to each tub in Week 5 indicated that most feedstocks were not yet acceptable. Over the following week worms only survived in 3A and 6B (the two 4:1 Cardboard:DAF treatments). The survival of worms in these tubs indicated that a higher cardboard content made the feedstocks acceptable to *E. fetida* sooner. Tubs 3A (4:1), 5B (3:1) and 6B (4:1) were the fastest to be inoculated. Trends in pH, EC and NH_3 indicate these treatments had more favourable conditions for *E. fetida*, although as discussed in Section 3.4.1.3, one factor alone is not enough to determine feedstock suitability.

Initially, only one set of replicates was intended to be analysed throughout the trial. In Week 7, it first was noted that the pHs of the 3:1 replicates were different to each other, despite being set up identically. The pHs of the 2:1 and 4:1 treatments were close to their respective replicates. Tub 2A matched the 2:1 treatments (1A and 4B), while Tub 5B matched the 4:1 treatments (3A and 6B). In Week, 8 EC testing was introduced and a difference between the 3:1 replicates was again noted. In Week 11, NH_3 testing was

introduced and again, a difference between the 3:1 replicates was noticed. The polarity in the 3:1 treatments was surprising. It is unlikely these differences were caused by incorrect preparation of the 3:1 feedstocks as the same mass-based process was used to prepare all treatments and cross-contamination was minimised or eliminated. The initial (Week 0) results demonstrating the decline in EC with increasing cardboard also provide support for the 3:1 treatments having been prepared correctly (Figure 3-14). By Week 10 (within one week), the worms had moved into tubs 3A, 5B and 6B (both 4:1 and one 3:1 treatments, see photo R in Figure 3-23). At this stage, the odour of NH_3 was detectable in tubs 1A, 2A and 4B. This did not necessarily indicate that NH_3 content was the reason these feedstocks were inhospitable, as NH_3 was detectable in al tubs in Week 5, yet test worms survived in both 4:1 treatments.

Overwatering damaged the *E. fetida* populations in all tubs. This is clear from the large reduction in total worm biomass since inoculation (almost half the initial total biomass). Conditions appeared to improve in the tubs as the leachate evaporated, however, this is only obvious in the reduced NH_3 results. Neither pH nor EC appeared to change as the leachate evaporated.

Increasing the ratio of cardboard in the initial feedstocks decreased the EC. Initially, it was assumed that the EC in the pH in the feedstocks would have been tolerable for *E. fetida*, though the EC may have been too high. However, given the relevant discussion in Section 3.4.1.3, this may not have been the case as other factors such as pH, TOC, TKN and C:N also influence feedstock acceptability.

As in Blesa Marco *et al.* (2023) and Dume *et al.* (2023), EC increased by the end of the trial, although there was an initial decrease in all tubs. This was recorded in Tub 2A from Week 8-13 and in Tubs 1A and 4B from Week 8-16. EC in all tubs slowly increased until Week 36 (mixing) where it increased rapidly. Dume *et al.* (2023) showed that EC tracked every 30 days for 120 days increased across a range of feedstocks. All feedstocks in their experiment started with initial ECs of 0.7 dS/m, but C:N varied from 6 to 38:1. As noted above, the differences in EC in Week 8 were significant between the 4:1 (higher C:N) and 2:1 (lower C:N) treatments. Interestingly, Dume *et al.* (2023) showed a significant difference in EC between their highest and lowest C:N vermicomposting treatments after 30 days (approximately 1.3, 1.1, 0.5 and 0.5 dS/m for C:Ns ranging from 6 to 38:1). By the end of their experiment, EC was approximately 2.2 dS/m for the highest two C:Ns and 2.4 dS/m for the lowest two C:Ns. The difference between the two groups was significant. Conversely, the final ECs for the main trial vermicomposts were higher

in the 4:1 than the 2:1 treatments, though statistical analysis was not able to be performed on the data as only two replicates were used.

Compared to composting treatments (no worms), final EC content was much less variable and showed a stronger trend of increasing over time, in the pilot trial. The final compost EC tended to be related to the initial C:N despite all feedstocks starting with the same EC (0.7 dS/m). Blesa Marco *et al.* (2023) also reported a statistically significant effect of *E. fetida* on EC where *E. fetida* presence resulted in higher ECs. In a study on *Eisenia euginiae*, Biruntha *et al.* (2020) also reported a significant increase in EC by the end of vermicomposting and that *E. euginiae*'s presence resulted in higher EC than composting alone. The increase in EC in the last four weeks of the main trial may have been due to both drying of the feedstock (concentration of salts) and mineralisation occurring due to physical disturbance (allowing microbes access to new resources).

As NH_3 acts as a weak base in solution, its presence increases pH. Both pH and NH_3 contents of Tubs 1A, 2A and 4B (both 2:1 and one 3:1 treatment) were noted to be higher than Tubs 3A, 5B and 6B (both 4:1 treatments and one 3:1 treatment) in the early weeks of monitoring. However, pH was recorded to be elevated between Week 7-14, while NH_3 was recorded to be elevated between Week 11-18. Ideally, NH_3 contents <0.05 mg/kg are best for *E. fetida* to thrive (Edwards, 1985). NH_3 in this experiment was measured using calibrated dipsticks which gave an indication of the level of NH_3 based on colour. While this was not an accurate measure of the actual amount of NH_3 present in the feedstocks, it gave a comparison between treatments. Although the following data is not accurate, it can be used as an indication of NH_3 toxicity. Out of interest, the numeric values of the NH_3 data were converted from mg/L to mg/kg of fresh feedstock by dividing the concentration of NH_3 in mg/L by the feedstock weekly bulk densities in kg/L. This exercise showed that all measured values including the minimum measurable concentration of 0.5 mg/L on the dipsticks were greater than the recommended threshold of 0.05 mg/kg. In short, any time NH_3 was detected at any level on the dipsticks, the concentration of NH_3 in mg/kg feedstock exceeded *E. fetida* tolerances. Despite this, *E. fetida* populations did increase.

While not the focus of their study, data reported in Gunadi and Edwards (2003) show that cattle and pig solids from different sources had varying NH_4^+ contents. In their study, there was no pattern in NH_4^+ content and mortality rate. Very interestingly, the feedstock with the highest NH_4^+ content (sow pig solids, 1,424.4 mg/kg) had the lowest mortality rate (22%) and the feedstock with the lowest NH_4^+ content did not support *E. fetida*. pH results were not reported in this trial.

Feedstock height was measured weekly from Week 8 onwards. Bulk density was calculated from these measurements. Averaging across treatments, bulk density ranged slowly declined from 680 g/L in Week 8 to 645g/l in Week 36, before dropping to 444 g/L in Week 37 after the Week 36 mixing event and finally to 370 g/L in Week 40.

3.4.2.2 Moisture content, leachate production and worm health

A study by Gunadi *et al.* (2003) tested five different moisture contents ranging from 70-90% on separate cattle and pig manure feedstocks. The initial aim of the main trial was to maintain a moisture content of 80-85% as this was recommended in literature e.g. Gunadi *et al.* (2003), and was similar to the initial DAF moisture content. Initially, it was not possible to achieve the same moisture content as the DAF sludge as the cardboard held less water at saturation. This is unsurprising given the nature of cardboard such as its smooth surfaces and limited surface area (compared to pre-production pulp fibre, for example).

Drainage had not been incorporated into the trial design as the intention was to retain all nutrients (except gaseous losses) and it had not been necessary in the pilot trial. In the pilot trial, worms were observed to spend time in or move through leachate at the bottom of the containers. It did not appear to harm them. The ability of the feedstock/vermicomposted material to hold water was expected to change with time.

Prior to inoculation of *E. fetida*, the water applied to the feedstocks each week was mixed in by hand. The initial watering method brought the total mass of the feedstock in each tub back to its original mass between Weeks 0 and 18. This method kept the feedstock moist and was assumed to maintain a relatively equal moisture content between tubs, though this was not regularly measured. After inoculation (beginning Week 10), mixing stopped, but the watering regime remained the same. It was also assumed that the worms would mix the water and feedstock together. This did not occur and eventually led to the production of leachate at the bottom of the tubs.

Over time the total feedstock DM decreased due to decomposition (and the removal of material through weekly sampling for EC and pH). The MC was noted to increase to an average of 85.7% (range 84.9-85.7%) by Week 21. A similar average moisture content of 85.0% (range 83.4-86.2%) was measured at Week 25.

As leachate volumes increased, worm health declined. Some worms were found with damage to the lower halves of their bodies as if segments had been cinched. Individuals may have been suffering from sour crop, also referred to as protein poisoning and string of pearls (due to the appearance of the afflicted worms). No formal scientific

research appears to be available on this condition, though practical vermiculture guides and forums discuss the topic. Research into this condition indicate it is a reaction to environmental conditions (too much food leading to protein build up in bedding material) and not a communicable disease, although it is fatal. Apparently, if not enough calcium is available, high protein, feeds are not neutralised in the crop and acidic feed can ferment in the gut, causing a build-up of gases and eventual rupture of the intestine (Urban Worm Company, n.d.). While the feedstocks were not especially acidic at the time the worms were affected, there was an abundance of high-N food (DAF sludge) available due to the batch-fed trial design. It is interesting that conditions in the main trial were similar to the pilot trial in regard to the watering schedule, stocking rate (0.1 worms/g DM) and leachate production. However, worms in the pilot trial did not exhibit signs of sour crop. The feedstocks appeared to behave dissimilarly e.g. with the formation of anoxic zones in the main trial tubs as noted in Week 36 after mixing. The differences between the trials also extend to the calcium content of the cardboard, which was noticeably higher in the pilot trial (128.93 mg/kg) than the main trial (20.13 mg/kg, below QL) and may have contributed to protecting the pilot trial worms from developing sour crop (Urban Worm Company, n.d.). The differences in the cardboards demonstrate that nutrient contents of organic inputs often differ and care needs to be taken when considering different inputs as feedstocks.

3.4.2.3 Vermicomposts compared to NZS 4454:2005

The main vermicomposting trial produced vermicomposts, not vermicasts. The White Gold product used in the plant production trials, is also classed as a vermicompost, rather than a vermicast. Time constraints meant the vermicomposting trial had to end after 40 weeks. Ideally, they would have been left to vermicompost to completion (until they were truly vermicasts). Forty weeks is longer than was anticipated for this trial, but as explained in Section 3.4.2.2., overwatering led to population decline and this affected the speed of vermicomposting. Despite this, the vermicomposts produced passed most of the tests for NZS 4454:2005, including the plant growth index test that is not required for vermicasts or vermicomposts, but demonstrates the value of a product for plant growth.

3.4.2.3.1 Particle size grading

All trial vermicomposts failed the particle size grading test that determines whether the products are vermicasts or vermicomposts. The 4:1 treatments (Tubs 3A and 6B) and one of the 3:1 treatments (Tub 5B) had almost four times as much vermicast (average 28.0%) than the 2:1 treatments (Tubs 1A and 4B) and the other 3:1 treatment

(2A) (average 7.6%). This gave a clear indication that Tubs 3A, 5B and 6B were more processed than the other treatments.

The White Gold vermicompost had the highest proportion of vermicast (47.1%), but this was not high enough to meet the 90% threshold stipulated in the Standards. As the industrial vermicomposting process used to produce the White Gold product was outdoors in direct contact with the soil, it is possible that soil contamination occurred during processing, through earthworm movement and processing, or at collection of vermicast with loader buckets where soil was also collected.

3.4.2.3.2 Ash/volatile solids content

The ash content increased substantially; 242.7%, 261.0% and 229.4% (2:1, 3:1 and 4:1 treatments, respectively). However, the reduction in VS in the vermicomposted feedstocks was small (-12.5%, -11.4% and -9.1% for the 2:1, 3:1 and 4:1 treatments, respectively. This could have been due to lignin from the cardboard resisting degradation, though its content was not measured (Mboowa, 2024; Vikman *et al.*, 2024) and the fact that the feedstocks had not been fully vermicomposted – they were not yet vermicasts and could have decomposed further. However, the reduction is within the 7.6-15.2% reduction range that Hait and Tare (2011) reported for vermicomposted WAS + vermicompost feedstocks. They also reported the reduction in VS was greater for vermicomposting vs composting treatments, however, it was not clear whether the difference was significant. Frederickson *et al.* (1997) reported vermicomposting treatments significantly reduced VS compared to composting treatments over the same period of time. It was not clear from the methodology whether treatment replicates were taken from the same experimental units. Also, given the low standard deviations reported, it is possible pseudo replication occurred in which case it is not possible to confirm the significance of the VS results relative to the composted treatments.

The White Gold vermicompost had a much lower (22.3%) VS content than the trial vermicomposts. Prior to testing, it had been in storage for two years and may have continued slowly decomposing, reducing the organic matter fraction (VS) and leaving a higher mineral (ash) content behind. The low ash content, high volatile solids of the trial vermicomposts versus the industrially produced vermicompost indicate the trial vermicomposts were dominated by organic material. The high ash content, low volatile solids content of the industrially produced vermicompost indicate that as well as being well-vermicomposted, the feedstock for this material may have had a high mineral content, or that contamination of the feedstock/finished product may have occurred during the

process e.g. soil may have also been picked up vermicast was harvested from the outdoor windrows.

3.4.2.3.3 Large particle contamination

Two treatments (1A and 2B) failed the test for large particle contamination. This was the fraction of vermicompost that did not pass through the sieve after washing under running water while breaking up material by hand for a maximum of 10 minutes. Cocoons, unprocessed cardboard, plastic film and small, hard dark brown lumps of unprocessed feedstock were the material that remained. They were the same materials found in the other feedstocks when tested, but in greater volumes. These particular remnants are a clear indication that the feedstocks (1A and 2A in particular) needed longer to finish processing.

3.4.2.3.4 Bulk density

Bulk density was required as a test under the Standards, but no thresholds were stated for this test. The trial vermicomposts had lower BD (520 g/L on average) than the White Gold vermicompost (820 g/L). Zaki *et al.* (2017) reported that vermicompost bulk density graded to three particle sizes (0.3, 0.6, 1.18 mm) decreased with increasing particle size (~790, 750 and 690 g/L, respectively). While the vermicomposts in the main trial all contained material >1.18 mm (see particle size grading results), this trend fits with the observations made in the vermicomposting trial. While the differences were small, Tubs 1A and 2B had the highest large particle contamination rate and also had the lowest bulk densities.

The White Gold vermicompost also had a high ash content (77.7%) could explain why it had a higher bulk density than the trial vermicomposts as ash tends to have a higher specific gravity than organic matter (Enemo *et al.*, 2025).

3.4.2.3.5 Chemical properties

Both pH and EC throughout the vermicomposting period have been discussed in depth. The pH and EC results discussed here are the final measurements of the vermicomposts. Except for Tub 3A, one of the 4:1 treatments, the pHs of the vermicomposts were all within the range required by the Standards (5.0 to 8.5). The White Gold pH was close to neutral (7.1). Low pH in the trial vermicomposts is not unexpected as organic acids and CO_2 are released during decomposition (Sharma & Garg, 2018). According to Domínguez and Edwards (2004), epigeic earthworms (such as *E. fetida*) prefer more acid material (pH 5.0). The White Gold vermicompost may have had a pH

close to 7 due to its feedstock inputs and/or its age (>2 years at the time of testing). In the trial vermicomposts, pH decreased with increasing cardboard content while EC tended to increase. There is no limit for EC of vermicomposts, however, a secondary table within the Standards gives maximum application rates for products incorporated into the soil to a depth of 5 cm. At <1.0 dS/m, there are no limits for product application. None of the trial vermicomposts (or the White Gold) meet the criteria, so there are application limits for all products. Tubs 1A, 2A and 4B are limited to <15 L/m^2 (75 t FM/ha, based on BD) for saline-sensitive plants and <60 L/m^2 (300 t FM/ha) for saline-tolerant plants. Tubs 3A, 5B and 6B are limited to <8 L/m^2 (43 t FM/ha) for sensitive plants and <32 L/m^2 (170 t FM/ha) for tolerant plants. The White Gold would be limited to application rates of 66 and 264 t FM/ha for sensitive and tolerant plants, based on EC alone.

The minimum moisture content permitted in the Standards is 25%. All treatments were well above this. Moisture is required to support life and given a significant portion of the value in vermicompost is in its microbial activity (Standards New Zealand, 2005), maintaining a reasonable moisture content is important, though for transport, a lower moisture content would be desirable (less water to transport/sell as product).

The chicken DAF appeared to exceed both the 2003 and 2005 limits for Cd, though this was detected below quantitation limits – the same as for the pilot trial. However, unlike the pilot trial, the cardboard did not appear to be a source of Cd. This is reflected in the results for the pure cardboard and the mixed feedstocks as Cd was not detected in either. At the conclusion of the trial, Cd content was below quantitation limits (results should be interpreted with caution) and below the 2003 and 2005 land application guidelines. These results indicate that the source of cardboard/paper waste could be an important factor in controlling elevated heavy metal contents in organic wastes as there appeared to be a dilution effect in the initial feedstocks (Cd was only detected in the pure DAF sludge). By the end of the trial, Cd was present in all vermicomposts, again below quantitation limits, but also below the 2003 and 2005 land application limits. The presence of Cd in the vermicomposts but not the initial feedstocks indicates that the heavy metals concentrated as the feedstock volume decreased during the vermicomposting process. Whether there was a bioaccumulation effect of *E. fetida* is unknown as no testing was done on worm biomass. See Section 3.4.1.2 for further discussion on Cd.

3.4.2.3.6 Biological properties

All the vermicomposts had ECs 2.5 or less, meaning leaching was not required to test their toxicity prior to sowing the radish seeds. None of the vermicomposts tested were

toxic to radishes. All outperformed the Dalton sand control, including the additional treatments of vermicompost broadcast or incorporated at 12.5 t FM/ha. The most beneficial treatment was the pure vermicompost. White Gold grew the greatest average root length (102 mm). The least beneficial treatment was the incorporated treatment, though this still outperformed the Control. The broadcast treatment is assumed to have performed better than the incorporated treatment due to the close proximity of the broadcast vermicompost (spread on top) to the seeds (just below the surface). While the incorporated treatment had the same quantity of vermicompost as the broadcast treatment, it was mixed into the sand to the full depth, diluting it.

There is not a recommended timeframe for initiation of the plant propagule testing. This trial was started five weeks after the vermicomposting trial ended as it was not practical to start at the time of year that the trial finished. The weeds that germinated in the White Gold vermicompost (known to contain weeds due to long periods of vermicomposting outdoors and no process e.g. heat treatment to sterilise seeds/propagules) had been dormant during the two years of storage. The inputs used as feedstock for the main trial should not have contained any plant propagules, therefore the conclusion of this trial is that the vermicomposts produced were free from plant propagules.

Testing for plant growth index (PGI) is not required for vermicomposts (or vermicasts) under the Standards. It was included in the testing regime to determine the vermicomposts value for plant production. Testing for PGI is recommended to occur within seven days of collection. However, at the time of year the trial finished, it was not practical to begin this trial (or the plant propagule trial), so samples were stored in a large plastic box in an air-conditioned room in plastic ziplock bags with ventilation holes poked into them for six weeks. This complied with the recommendation for sample storage in laboratories after receipt before testing in the Standard (section 2.6.1.1).

The results of the PGI trial showed that the trial and White Gold vermicomposts had a beneficial effect on tomato plant growth. The greater the concentration of vermicompost in the growing media, the faster and stronger the tomato plants grew. Both over and underwatering were issues during the trial as an automatic irrigation system was used to maintain the trial. Unexpected cooler temperatures reduced evapotranspiration early in the trial leading to overwatering and leaching of nutrients. Later in the trial, the difference in growth between the pure vermicompost and 1:1 mixes as compared to the broadcast and Control treatments lead to differences in evapotranspiration between treatments with the former tending to be underwatered. This was addressed by topping up the larger plants to avoid wilting. Although occurrences of wilting would have affected

the total potential growth of the larger plants, they still well outperformed the Control and broadcast treatments.

The 1:1 White Gold treatment performed surprisingly poorly compared to the 1:1 trial vermicomposts. Based on the results of the radish germination trial and the broadcast PGI treatments, the older, industrially produced White Gold vermicompost was expected to perform as well as the fresher trial vermicomposts. This was not the case as the 1:1 White Gold tomato plant performed no better than the broadcast vermicompost treatments. Given the White Gold vermicompost had much lower nutrient value than the fresh vermicomposts, this is not necessarily surprising and indicates that the White Gold vermicompost has value for seedlings, but is not sufficient to support larger plants in a growing media that is 50% sand. However, field trials in Chapter 5 using the same vermicast showed beneficial effects on commercial onion crops.

3.4.2.3.7 Microbiological properties

No pathogens were detected in the trial vermicomposts (White Gold is excluded as it was not tested). As two lots of testing were required for the vermicomposts, it is possible that *E. coli* numbers declined in storage between the two tests. However, given the initial test results were below detection limits, this was considered unlikely. In addition, the <10 cfu/g faecal coliform result from the pilot trial DAF sludge supports the suggestion that the sludge was sanitary to begin with and (assuming no contamination occurred during vermicomposting), the final *E. coli* results are trustworthy.

In addition, a discussion about wastewater treatment management was had (with a different processing plant to the facility the DAF sludge was obtained from). At this other plant, pathogens are monitored in the wastewater treatment process for internal purposes. Their anaerobic storage pond is occasionally tested for Salmonella, but the irrigation storage pond is tested weekly for pathogens (faecal coliforms and Salmonella). In their facility, pathogens should not be an issue in processing wastewater as the waste from the processing facilities should be clean (Artika Devi, personal communication, July 15, 2025). Despite evidence that vermicomposting also sanitises feedstocks (Swati & Hait, 2018), the lack of pathogens in the vermicomposting feedstock may therefore not be surprising.

3.4.2.3.8 Foreign material contamination

The plastic contamination from the cardboard was surprising as it was not detectable until later in the vermicomposting stage. This is what caused the trial vermicomposts to fail the test for foreign material contamination. No tests were

performed on the biodegradability of the plastic and the supplier/manufacturer could not be reached for comment on the unexpected liner. The issue of the plastic contamination could be overcome by using a different cardboard/carbon source (there was not plastic contamination in the pilot trial, for example. While the contamination was noticeable, it may have been less severe than reported (the mass of the plastic film could have been slightly increased due to the difficulty of removing the cardboard from some particles, though this would not have reduced the contamination below the Standards' threshold). The Standards also state that "suppliers and customers are advised to agree on an acceptable maximum level of visual contamination of lightweight plastics" (Standards New Zealand, 2005). In a reality where contamination of industrially produced compost products (e.g. via glass, plastic, metal) is widespread, this could be interpreted as a caveat allowing higher contents of contamination in composts/mulches/vermi products, though this is not a desirable outcome.

The presence of plastic is undesirable given the known and unknown effects of microplastics (<5 mm plastic particles) in soil and the food chain. Microplastics have been shown to be taken up by plants e.g. polystyrene in wheat and accumulate in their vascular systems (Li *et al.*, 2023). They have also been shown to inhibit water and nutrient uptake, cause oxidative damage and disrupting metabolic activities, cause/enhance toxic effects and alter soil environments (Iqbal *et al.*, 2023). In a study on PET and PVC added to soils growing tomato plants, Dainelli *et al.* (2023) showed that while the presence of microplastics at environmentally relevant rates (0.5% microplastic/soil w/w) had marginal effects on growth and physiology, they decreased the number of fruits and PVC reduced the fresh fruit weight. Both forms of microplastic were reported to lower fruit quality in terms of nutritional value and increased the concentration of Ni and Cd in the fruit. Ideally, a plastic-free source of carbon/fibre would be used to produce high-quality vermicast/vermicompost. However, the addition of microplastics from a contaminated vermicast/vermicompost may supply far less microplastic loading to soils than for crops grown under plastic mulches.

Prior to delivery (and storage and use in the trial), the White Gold product was screened to 2 mm. It comprised 4% foreign material, mostly stones with some rigid plastic pieces. This was below the threshold of 5% (for stones and lumps of clay, 4% for rigid plastics) but close to a fail. Overall, the material was 'siltier' than the trial vermicomposts. This, along with the high ash (77.7%), low volatile solids (22.3%) contents indicate that of the material passing through the 1.18 mm sieve, perhaps not all of it was vermicast. However, this cannot be confirmed as the inputs of the White Gold were different to the

trial vermicomposts and therefore it is reasonable to expect variations in texture and other parameters.

3.4.2.4 Summary relating to the Standards

The voluntary Standards have not been updated since they were released in 2005. There would be value in having an updated version. Wakim (2001) provided a template for vermicompost guidelines for New Zealand and recommended regular updates as the industry develops. An updated version would benefit from the inclusion of microbiological tests, clarity in testing methods for specific products and new guidelines for heavy metal application (given the updated biosolids application guidelines). Some recommendations have already been made within the document in anticipation of regular updates: "it is expected that the toxicity test (Appendix D) for pasteurised soil conditioners, etc. will be upgraded in future by including a sand control, or changing to a plant growth test with an index of >1 (less stringent than the stipulated >2 for composted products)"(Standards New Zealand, 2005). However, since its publication, no further versions have been released. This may be due to the Standards being a voluntary guideline, rather than a mandated industry norm.

3.4.2.5 Other observations

Odour was a significant characteristic of the DAF sludge. Until it had been decomposed/vermicomposted, it was extremely pungent and offensive. This kind of organic waste could cause significant nuisance problems with if vermicomposting production was scaled up. It is recommended that controls for odour are planned. This could include a pre-composting stage to rapidly degrade the odorous material (considering that this could also produce odorous gases), limiting the total amount of DAF sludge vermicomposted per batch, using a higher cardboard/fibre content relative to the DAF sludge and/or covering the DAF sludge to minimise odour emissions. By the time the products were vermicomposts, this odour was not an issue.

Weekly feedstock EC and pH were tested using a 1:5 w/v extraction rather than 1:1.5 v/v extraction as per NZS 4454:2005. The 1:5 w/v extraction is accepted in literature and provided sufficient solution volume for the probes and minimised the amount of feedstock removed from the tubs each week, while still allowing a reasonable representative subsample. Following the NZS 4454:2005 method would have used too much feedstock over the 40-week trial period.

3.5 Conclusions of both vermicomposting trials

Vermicompost compliant with the New Zealand Standards was able to be produced from chicken processing DAF sludge and cardboard feedstocks at the ratios tested in a controlled environment. When tested against the Standards, a few tests were failed: the presence of a plastic film contaminant from the cardboard in all main trial treatments; one Tub having a pH <5.0; and two Tubs having >10% large particle contamination. Otherwise, the vermicomposts passed all tests required by the Standards (although none had processed enough to be classed as vermicasts).

Cardboard was a necessary addition to chicken processing DAF sludge for successful processing. This was true both for the vermicomposting treatments (with *E. fetida*) and composting treatments (without *E. fetida*). Higher cardboard content appeared to be beneficial for speed of inoculation, supporting worm population growth and producing vermicompost with a higher vermicast proportion.

Correct feedstock moisture content was essential as it strongly influenced worm activity. When overwatered, attractive feedstocks became toxic environment, reducing worm populations and affecting the speed of the vermicomposting process, though the trial was recoverable.

The two trials presented here demonstrate that if mixed with enough cardboard, DAF sludge can support *E. fetida* and be processed into a beneficial soil conditioner. However, contamination via the cardboard source is an important consideration. Although a ‘clean’ rather than non-recyclable cardboard source was selected for the main trial, plastic contamination caused the vermicomposts to fail the NZS 4454:2005 test for contamination of foreign material.

While no statistical analyses are possible due to the limited number of replicates, the results and descriptions can be used to scale up the trial to commercial quantities.

Chapter 4

Plant production: glasshouse trials

Vermicast[4] derived from milk processing dissolved air flotation (DAF) sludge and pulp and paper mill solids (fibre) was applied to onions (*Allium cepa* L. cv Rhinestone) under glasshouse conditions. The effectiveness of vermicast at increasing onion size and mass was compared to a control treatment. Three trials were conducted, investigating:

1. the timing of the application of vermicast at 12.5 t FM/ha/yr on the same cropping soil as used in the Matamata field trials in 2023-2024,
2. a repeat of the above trial on a low Olsen P soil from Ohakune in 2024-2025, and
3. whether vermicast could be used to supplement phosphorus (P) on a low Olsen-P soil from Ohakune in 2024-2025.

Due to similarities in the trial designs and aims, this chapter is structured so that the methodology and results of the each of the three trials are reported in the same major sections (Methods, Results and Discussions), but reporting is done in chronological order. As Trials 1 and 2 were very similar in design, Trial 2 methods refer back to Trial 1, but deviations are noted. As Trials 2 and 3 were run concurrently, some parts of Trial 3's methods including tables are cross-referenced to Trial 2.

Note: the following trials did not use vermicast produced in the Chapter 3 trials. The pilot vermicomposting trial did not produce enough vermicast for the glasshouse trials and the main vermicomposting trial was started after the glasshouse trials were finished. However, the vermicast used in the glasshouse trials was subsampled from the same batch used in the three-year field trials in Matamata. A subsample of the vermicast from the Matamata field trials (see Section 5.4.1.1) was used for all three glasshouse trials.

4.1 Background

While the following trials began after the trials described in Chapter 5, they are reported first as they investigate the effects of the same vermicast under controlled conditions. Three trials were conducted to investigate the effects of vermicast application to onion crops. Trial 1 was a glasshouse trial designed to assess the effect of the timing and application method of vermicast on seedling emergence, bulb size, mass, overall yield and root dry matter (DM) production. This trial was run concurrently with the onion crop

[4]The White Gold vermicast tested in Chapter 3 was deemed to be a vermicompost, not a vermicast under the voluntary NZS 4454:2005 composting standards. However, as the White Gold product was received and used in this trial as a vermicast, it will be referred to as a vermicast in Chapters 4 and 5.

grown in the second season in Matamata (see Chapter 5). Trials 2 and 3 were run concurrently a year later, in the same glasshouse. Trial 2 was a repeat of Trial 1 on a different soil. Trial 3 was designed to investigate the potential for vermicast to supplement reduced rates of phosphorus (P) fertiliser. The effects on bulb size, mass, yield, root DM production and final soil Olsen P were analysed.

4.2 Methods

4.2.1 Trial 1: 2023-2024 timing of vermicast application trial

The purpose of this trial was to understand whether the timing of a single 12.5 t FM/ha broadcast (surface applied) vermicast application could affect final onion yield e.g. would there be a difference in yield if the vermicast was applied at sowing, versus three months post-sowing? The trial also included one treatment of vermicast incorporated into the soil at sowing (Table 4-1).

Six vermicast treatments were applied. Treatment effects on onion size and mass were compared to a non-vermicast control. The treatments are reported in Table 4-1 and depicted in Figure 4-1.

Table 4-1: Treatments for the 2023-2024 timing trial and vermicast application dates. The first character (number) in the treatment label denotes the month post-sowing vermicast was applied (0, 1, 2… i.e. the timing of the application). The second character (letter) denotes the method of application (B = broadcast (surface applied), I = incorporated). The third character (number, generically referred to as 'X') denotes the replicate (1-4) for the treatment. See Figure 4-1 for diagrammatic representation.

Treatment	Description	Application date
Control X	No vermicast applied	-
0IX	12.5 t FM/ha incorporated at sowing	05/09/2023
0BX	12.5 t FM/ha broadcast at sowing	05/09/2023
1BX	12.5 t FM/ha broadcast one month post sowing	10/10/2023
2BX	12.5 t FM/ha broadcast two months post sowing	6/11/2023
3BX	12.5 t FM/ha broadcast three months post sowing	7/12/2023
4BX	12.5 t FM/ha broadcast four months post sowing	28/12/2023

Other than the vermicast applications, all experimental units were treated the same, including watering volumes and frequency. Each treatment was replicated four times. It was unknown how long the growing season would be for the onions in the glasshouse, so 12 additional experimental units were prepared and maintained through the trial for months five onwards, but these did not receive vermicast and were not analysed at the end of the experiment. In total 28 experimental units (pots) and one additional 'dummy' were used.

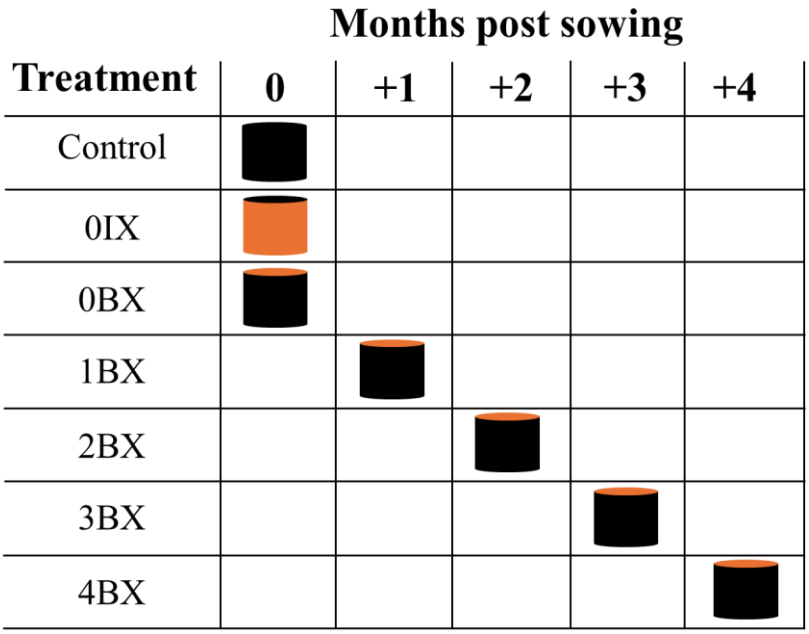


Figure 4-1: Representation of timing of vermicast applications. Pots are represented by cylinders. Vermicast application is represented by the orange colour (cylinder coloured orange = vermicast incorporated into soil, top of cylinder coloured orange = vermicast broadcast/surface applied). See Table 4-1 for treatment details.

4.2.1.1 Trial 1 set up and onion sowing

Soil was collected from an area adjacent to Season 2 Trial C from the Matamata field trials (Chapter 5). This soil (Typic Orthic Allophanic) was the same as that of the existing trial but was uncontaminated with vermicast/chicken litter. See Section 5.5.1 for soil details. Prior to collection, the soil had been fertilised with 500 kg/ha Serpentine Super 7k (see Section 5.3) on 9 August 2023. A week later, a total of 720 L was collected to a depth of 230 mm (the depth of the pots used in the glasshouse trial) using a spade. A sample of pelletised Rhinestone seed (the same as what was sown in Trial C) was collected for use in the glasshouse trial. The soil and seeds were transported to the University of Waikato in Hamilton, North Island, New Zealand (37.7922° S, 175.7732° E). The soil was stored in 120 L plastic wheelie bins in a building next to the glasshouse the trial was to be conducted in.

In early September 2023, subsamples of soil mixed from different wheelie bins were sieved to 12 mm and bulked as an initial mixing step. Most of the material removed was maize stalks from the previous crop and some potato tubers. On 4 September 2023, the sieved soil was homogenised in a 650 watt, 160 L concrete mixer in 20 L batches for one minute per batch. The homogenised soil was poured onto a tarpaulin in thin layers, forming an approximately 2 x 1 x 0.5 m^3 pile in a glasshouse.

The glasshouse for the experiment was equipped with an automated control system connected to automated shade screens, ventilation and evaporative cooling. Glasshouse environmental control was set to prevent daytime temperatures from exceeding 30°C.

On 5 September 2023, 30 black plastic (220 mm deep, 240 mm diameter) 10 L pots were filled with 9.5 L of the homogenised soil and dropped from a 100 mm height to pack slightly and the surface smoothed out by hand. Four separate 9.5 L lots of soil were individually mixed with 47.8 g vermicast in the concrete mixer for 1 minute. The homogenised soil/vermicast material was decanted into four individual 10 L pots and dropped from a 100 mm height to pack and the surfaces smoothed by hand, as for the previous pots.

A stamp made from a wooden block with six holes drilled through the block to fit bolts with 2x 6 mm nuts on the end was pressed into the surface of the soil in the pots. This left 6x 2 mm indentations on the surface. The spacings for seed placement was based off the field trial spacing of 62 mm between seeds in a row and 100 mm between rows. In the 240 mm diameter pots, this made two rows 100 mm apart with three indents 62 mm apart. The first 46 non-vermicast pots were stamped first to avoid vermicast cross contamination. Two pelletised onion seeds (individual seeds encased in a pellet containing fertiliser) were placed in each hole and 250 mL leftover soil was applied to the surface of each pot, smoothed out and pressed lightly to cover the seeds. For the four pots (0B1-0B4) receiving broadcast vermicast at sowing, 47.5 g vermicast was sprinkled over the entire surface area of each pot.

Representative subsamples of vermicast and soil were collected and double bagged in sealable plastic bags, then stored in polystyrene boxes until analysis.

Each pot was placed in a 300 mm diameter, 30 mm deep saucer to capture potential drainage and minimise soil loss from the base of the pots when randomising their placement on the tables. Initially, the pots were placed in a grid pattern next to each other on one table. Placement was random and determined by assigning a number to each placement on the table and allocating pots to placements using a random number generator. All pots were misted with water.

After the emergence trial, the pots were placed around the outside edges of three moveable tables. This was to minimise the risk of damaging onion leaves when pots were allocated to new random positions and to allow access to all areas of the soil surface when applying vermicast treatments, fertilising and watering.

4.2.1.2 Trial 1 emergence

Emergence was defined as the appearance of the onion cotyledon (flag leaf) from the soil surface. The rates of emergence for the Control, broadcast at sowing and incorporated at sowing treatments were recorded. Emergence began on 11 September 2023 and was recorded for each seed sown per pot (12 seeds per pot) twice daily until 22 September 2023. After emergence, seedings were thinned to six individuals per pot (without doubles). In some cases, neither seed in the planting holes had emerged so these pots received transplants from extra pots. The pots that received transplants were 0B1, 0I3, 1B1, 3B2, 4B3, Control 1 and Control 2.

4.2.1.3 Trial 1 watering and maintenance

Throughout the emergence trial, the surface of the soil was misted twice daily to maintain even soil moisture at the soil surface from sowing until the end of emergence on 25 September 2023 when watering increased as follows.

Field capacity was determined by selecting one pot and adding water slowly until drainage occurred. The pot was covered with a plastic saucer and left for 24 hours before weighing to the nearest gram. This pot was not used in the trial.

Each pot received the same amount of water every three days. The quantity of water to be applied every three days was the difference in water mass between a 'dummy' pot and the measured field capacity. The dummy pot was treated the same as the Control (onion seeds sown, no vermicast) and weighed before each watering. It was not used in the trial but received the same treatments as the Control including sprays and fertiliser. The following calculation was used to determine the amount of water to add to each pot:

$$Mass\ of\ pot\ at\ field\ capacity - mass\ of\ dummy\ pot = water\ to\ apply\ per\ pot$$

Weeds were managed by pulling and laying the weeds on the soil surface of their respective pots as they were noticed.

4.2.1.4 Trial 1 pest and disease prevention

Pests and diseases were prevented with fortnightly fungicide and insecticide applications to manage downy mildew (*Peronospora destructor*), white rot (*Sclerotium cepivorum*), *Botrytis*, *Stemphylium*, *Alternaria*, thrips (*Thrips tabaci*), onion maggot (*Delia antiqua*), cutworm (*Agrotis ipsilon*) and bacterial infections such as bacterial soft rot (*Erwinia spp.*) until the onions were pulled at the end of January 2024.

4.2.1.5 Trial 1 randomisation

Each week, the tables the pots were placed on were rotated 180° and their positions shuffled in the glasshouse to minimise environmental influences like sunlight exposure. Pot placements on the tables were also randomised weekly until December 2023 after which there was too much risk of damaging the leaves when moving the pots. The tables were still rotated and shuffled.

4.2.1.6 Trial 1 fertiliser application

A similar fertiliser regime to what was implemented for Trial C in the Matamata field trials was followed (see Table 5-2 and Table 5-5 for comparison). Fertiliser samples were obtained from Balle Bros Growers Ltd. Nutrient contents of the fertilisers are reported in Table 4-2. The application regime for the glasshouse trial is reported in Table 4-3. The mass of fertiliser to apply per pot was calculated using the following formula:

$$Fertiliser\ applied\ (g/pot) = \ pot\ surface\ area\ (m^2)\ \times\ application\ rate\ (\frac{g}{m^2})$$

The surface area of each pot was calculated to be 0.038 m^2.

Fertiliser was weighed for each individual pot and applied evenly across the surface of each pot by hand before watering on days when watering was due.

Table 4-2: Nutrient content of fertilisers used in the 2023-2024 timing trial. Nutrient content is reported as percent weight of element by product weight. N = nitrogen, P = phosphorus, K = potassium, S = sulphur, Mg = magnesium, Ca = calcium.

Fertiliser	N	P	K	S	Mg	Ca
Compound Extra	12	5.2	14	8	1.2	3.8
Compound Premium	12	5.2	14	8	1.2	3.8
DAP	18	20		1		

Table 4-3: Application dates, rates and quantities of fertiliser applied per pot in the 2023-2024 timing trial. Although not a fertiliser, the vermicast application rate is included.

Application date	Fertiliser	Rate (kg/ha)	Rate (g/m^2)	Quantity/pot (g)
2/10/2023	DAP	300	30	1.14
4/11/2023	Compound extra	300	30	1.14
7/12/2023	Compound premium	350	35	1.33
20/12/2023	Compound premium	350	35	1.33
See Table 4-1	*Vermicast*	*12,500*	*1,250*	*47.5*

4.2.1.7 Trial 1 vermicast application

As reported in Section 4.2.1.1, vermicast was applied at sowing in two treatments (0I and 0B. For months 1-4 post sowing, vermicast application dates are reported in Table

4-1. The application rate at 12.5 t FM/ha was equivalent to 47.5 g/pot, as per the following calculation:

$$Vermicast\ applied\ (g/pot) = \ pot\ surface\ area\ (m^2)\ \times\ application\ rate\ (\frac{g}{m^2})$$

Vermicast was applied evenly across the surface of each pot by hand before watering on days when watering was due.

4.2.1.8 Trial 1 harvest

When the leaves had folded (by 29 January 2024), the roots were cut at the base of the onions with scissors. The onions were left to dry for 15 days until 13 February 2024. Onion leaves were cut 15 mm from the top of the bulbs and discarded. For each onion bulb, its size class was determined using sizing rings (<40 mm = pickling, 40-60 mm = small, 60-80 mm = medium, >80 mm = large). Individual bulb mass was measured using a precision balance (Radwag® WTC 2000, WL-210-0001; readability 0.01 g).

Onion root dry matter (DM) was measured by inverting each pot over a stack of sieves with 19.00 mm, 13.20 mm and 4.75 mm apertures (top to bottom). Sieving was done gently, trying to keep the onion roots intact. Not all fine roots were able to be collected. The roots were stored with damp paper towels in individually sealed plastic bags. The next day, the soil was removed from the onion roots by hand. The roots were then rinsed over a 125 µm sieve to remove finer soil particles and minimise root loss. The roots were dried at 60 °C for five days before DM was weighed.

4.2.1.9 Trial 1 vermicast and soil analyses

Vermicast and soil samples were sieved to 2.00 mm and analysed for DM, pH, ash content/volatile solids, nutrient content and C:N. Vermicast was also tested for electrical conductivity (EC).

4.2.1.9.1 Dry matter analysis

Dry matter was determined by oven drying approximately 25 g vermicast at 105 °C for three days:

$$DM = \frac{dry\ mass}{field\ moist\ mass}$$

4.2.1.9.2 Vermicast pH and EC

Vermicast pH and EC were determined in a 1:5 extraction. A 10 ± 0.05 g field moist sample was shaken in 50 mL distilled water for 1 hour on an end-over-end shaker (1 revolution per second). A Eutech pH700 meter, calibrated to three points, was used to determine pH immediately after shaking. A calibrated Milwaukee MW 301 PRO EC meter (range 0-1990 µS/cm, equivalent to 0-1.9 dS/m) was used to determine EC.

4.2.1.9.3 Soil pH

Soil pH was determined for each sample following Blakemore *et al.* (1987) for pH in H_2O where 10 g soil was mixed with and then extracted in 25 mL distilled water overnight before testing with a calibrated pH probe.

4.2.1.9.4 Ash content/volatile solids

Vermicast and soil ash content were determined by oven drying a ~5 g sample at 105 °C until the mass was stable. The mass of the sample was recorded to 0.001 g and placed in a muffle furnace set to 550 °C for four hours. The remaining ash was weighed to 0.001 g and ash content/volatile solids determined by:

$$Ash\ content = \frac{ash\ mass}{dry\ mass}$$

$$Volatile\ solids = 100\% - ash\ content$$

4.2.1.9.5 Nutrient analysis

Soil and vermicast nutrients were determined using an Agilent 8900 Inductively Coupled Plasma – Mass Spectrometer (ICP-MS; Agilent Technologies, Santa Clara, California, USA) controlled by MassHunter Workstation (version 4.5). Samples were first dried at 50 °C for one week and ground in a ball mill grinder (a Retsch Mixer Mill MM 400) at 27.5 Hz for 60 seconds. Approximately 0.2 g of the ground samples were pre-digested overnight in reverse aqua regia (3:1 concentrated HNO_3: HCl) before digestion in a water bath set to 90 °C for 1 hour. Digests were then topped up to 50 mL with Type 1 water before a 15 mL subsample was filtered through a 0.45 µm filter. The subsamples were diluted 100x by taking 0.1 mL filtered digest, adding 9.7 mL Type 1 water and 0.2 mL HNO_3 to achieve a 2% HNO_3 concentration in the sample prior to analysis for Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, P, Pb, S, Sr, Tl, U, V, Zn.

4.2.1.9.6 C:N analysis

From the remainder of the soil and vermicast subsamples ground for ICP-MS analysis, a minimum of 2 g was submitted to Lincoln University for C:N analysis. Total carbon and nitrogen were analysed using an Elementar Vario-Max CN Elemental Analyser (Elementar GmbH, Hanau, Germany). The sample was combusted at 900°C in an oxygen atmosphere. The combustion process converts any elemental carbon and nitrogen into CO_2, N_2 and NO_x. NO_x are subsequently reduced to N_2. These gases were then passed through a thermal conductivity cell to determine CO_2 and N_2. Results were reported in elemental % as received. As DM was not tested directly on the C:N samples due to small sample sizes, a range of similarly treated samples were tested for DM and found to be 90% DM on average. This DM content was used to calculate C and N contents as %DM.

4.2.1.10 Trial 1 statistical analysis

The time to final emergence (days taken for all viable seeds to emerge) and the number of viable seeds were analysed using Kruskal-Wallis tests as data normalcy and assumptions of homogenous variance were not met. Analysis of variance (ANOVA) was used for analyses of onion mass, yield and root DM after checking for homogeneity of variance using Levene's test. As the data for size class contained many zero counts and sample sizes were small (n = 4 per treatment), Kruskal-Wallis and Dunn's tests were used rather than parametric tests like ANOVA where assumptions of normality and homogeneity of variance could not be met.

A post-hoc power test was performed for the seedling emergence data using G*Power (version 3.1.9.7). A one-way ANOVA ($\alpha = 0.05$) and observed effect size (Cohen's f) were used to determine achieved power. An a priori analysis ($1 - \beta = 0.80$) was then performed with power to determine the number of replicates required to detect a significant difference.

4.2.2 Trial 2: 2024-2025 timing of vermicast application trial

Trial 1 was repeated the following growing season (2024-2025) on a different soil. As the methods for Trial 2 were almost the same as Trial 1, this section cross references those under Section 4.2.1, above with variations such as fertiliser regimes stated.

Trial 2 (2024-2025 timing trial) and Trial 3 (phosphorus (P) supplementation) were run concurrently using a low Olsen P soil. To save on resources, the same three pots were used as the Control in both trials. Another three pots were used as the vermicast

broadcast (surface applied) at sowing (0BX) treatment from the timing trial and the vermicast + 100% P fertiliser (VP100) treatment from the P supplementation trial. While there is crossover between Trials 2 and 3, they are reported on separately.

4.2.2.1 Trial 2 set up and onion sowing

In Trial 2, four vermicast treatments were applied and compared to a non-vermicast control. The treatments are reported in Table 4-4 and depicted in Figure 4-2.

Table 4-4: Treatments for the 2024-2025 timing trial and vermicast application dates. The first character (number) in the treatment label denotes the month post-sowing vermicast was applied (0, 1, 2 i.e. the timing of the application). The second character (letter) denotes the method of application (B = broadcast, I = incorporated). The third character (number, generically referred to as 'X') denotes the replicate (1-3) for the treatment. See Figure 4-2 for diagrammatic representation.

Treatment	Description	Application date
Control X	No vermicast applied	-
0IX	12.5 t FM/ha incorporated at sowing	18/09/2024
0BX	12.5 t FM/ha broadcast at sowing	18/09/2025
1BX	12.5 t FM/ha broadcast one month post sowing	17/10/2024
2BX	12.5 t FM/ha broadcast two months post sowing	22/11/2024

Other than vermicast applications, all experimental units were treated the same, including watering volumes and frequency. Each treatment was replicated three times. As the trial was started later in the year than Trial 1, vermicast treatments did not go beyond two months post-sowing. In total 15 experimental units (pots) and four additional 'dummy' pots were set up.

Pelletised Rhinestone seed (leftover from Trial 1 i.e. of the same batch) was tested for germination before use in Trial 2.

Six hundred litres of soil, collected to a depth of 60 cm from an Ohakune drystock farm in autumn 2024 was stored in wooden boxes in a shed in Waharoa for two months. This soil is a representative of the Mangakahu family (Mans_20a.1 sibling (Manaaki Whenua, 2025c)), and is classified as a Typic Orthic Allophanic soil (Hewitt, 2010). In July 2024, the soil was transported to the University of Waikato in Hamilton, North Island, New Zealand (37.7922° S, 175.7732° E). It was stored in 120 L plastic wheelie bins in the glasshouse the trial was to be conducted in. Olsen P was tested on this soil on 5 July 2024 following Olsen *et al.* (1954) and Murphy and Riley (1962). Soil pH in H_2O was tested following Blakemore *et al.* (1987).

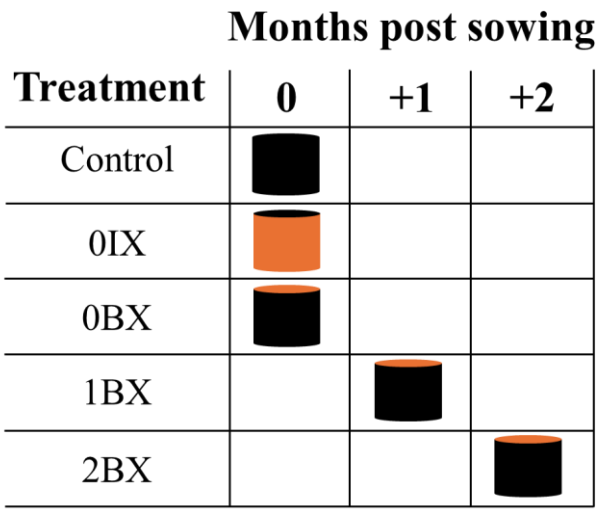


Figure 4-2: Representation of timing of vermicast applications. Pots are represented by cylinders. Vermicast application is represented by the orange colour (cylinder coloured orange = vermicast incorporated into soil, top of cylinder coloured orange = vermicast broadcast). See Table 4-4 for treatment details.

On 30 August 2024, the soil was sieved to 12 mm to remove Californian thistle rhizomes, couch grass rhizomes and small stones. Soil pH was adjusted by applying the equivalent of 6 t/ha Fertco G-lime (Farmlands) to 600 L soil on 30 July 2024. The soil was mixed in 20 L batches in a 650 watt, 160L concrete mixer. Each batch received 45 g lime and was gently sprayed with water until damp, but not sticky, while being mixed. After lime and water addition, each batch was mixed for one minute in the concrete mixer. The mixed soil was poured onto a tarpaulin in thin layers, forming an approximately 2 x 1 x 0.5 m3 pile in a glasshouse. The pile was watered with a hose as the surface layer dried over a 10-day period to allow the pH to adjust.

On 9 August 2024, the soil was tested for fertility and retested for pH by Hill Laboratories (basic soil test). A fertiliser regime was designed based on these results to prepare the soil for an onion crop. On 3 September 2024, 9.5 L of soil was measured into each pot (surface area 0.038 cm^2) and dropped once from a 100 mm height to pack slightly. Each pot was fertilised at a rate of 280 kg Muriate of Potash (MOP)/ha, 260 kg Calmag/ha and 500 kg Diammonium Phosphate (DAP)/ha (see Table 4-5 and Table 4-6).

The fertilisers were mixed into the soil. Each pot received 500 mL water, the equivalent of 13.2 mm rainfall and were rewatered again with 500 mL each on 9 September 2024.

The trial began on 18 September 2024. The soil in each pot was remixed by hand in a separate container and returned to its original pot. Twelve onion seeds were sown in each pot (six pairs of two) at 2 mm depth, with 250 mL soil spread over the top. Vermicast

was applied at a rate of 12.5 t/ha (47.5 g/pot) to 0B1-0B3 treatments. All pots were misted with water.

Representative subsamples of vermicast and soil were collected and double bagged in sealable plastic bags, then stored in polystyrene boxes until analysis.

Each pot was placed in a 300 mm diameter, 30 mm deep saucer to capture potential drainage and minimise soil loss from the base of the pots when randomising their placement on the tables. Pots were placed around the outside edges of three moveable tables (replicates 1, 2 and 3). Placement was random and determined by assigning a number to each placement on the table and allocating pots to placements using a random number generator. The tables holding the pots were rotated 180° and their positions within their respective tables shuffled approximately weekly. The layout was a randomised complete block design.

The trial was conducted in a climate-controlled glasshouse at the University of Waikato, Hamilton, New Zealand from 18 September 2024 to 20 March 2025. The glasshouse for the experiment was equipped with an automated control system connected to automated shade screens, ventilation and evaporative cooling. Glasshouse environmental control was set to prevent daytime temperatures from exceeding 30°C.

4.2.2.2 Trial 2 emergence

This trial was conducted similarly to Trial 1 (see Section 4.2.1.2). For Trial 2, the emergence trial ran from 27 September 2024 to 7 October 2024. After emergence, seedings were thinned to six individuals per pot (without doubles). No transplants were required.

4.2.2.3 Trial 2 watering and maintenance

Refer to Section 4.2.1.3. Three-daily watering began on 11 October 2024. Fresh dummy pots were used to calculate field capacity as the onions grew on 4 November 2024, 31 December 2024 and 9 January 2025. The original dummy pot was still weighed every three days to calculate the amount of water to apply. Some manual adjustment of this calculation was required later in the season to reduce the incidence of leachate.

4.2.2.4 Trial 2 pest and disease prevention

A pesticide and fungicide programme was initiated on 4 November 2011. See Section 4.2.1.4.

4.2.2.5 Trial 2 fertiliser application (side dressings)

Nutrient contents of the fertilisers are reported in Table 4-5. The application regime for the glasshouse trial is reported in Table 4-7. The mass of fertiliser to apply per pot was calculated using the following formula:

$$Fertiliser\ applied\ (g/pot) = \ pot\ surface\ area\ (m^2)\ \times\ application\ rate\ (\frac{g}{m^2})$$

The surface area of each pot was calculated to be 0.038 m^2.

Fertiliser was weighed for each individual pot and applied evenly across the surface of each pot by hand before watering on days when watering was due.

4.2.2.6 Trial 2 vermicast application

As reported in Section 4.2.2.1, vermicast was applied at sowing in two treatments (0IX and 0BX. Vermicast was applied to 1BX 1 month post sowing (17/10/2024) and 2BX 2 months post sowing (22/11/2024). The application rate at 12.5 t FM/ha was equivalent to 47.5 g/pot.

$$Vermicast\ applied\ (g/pot) = \ pot\ surface\ area\ (m^2)\ \times\ application\ rate\ (\frac{g}{m^2})$$

Vermicast was applied evenly across the surface of each pot by hand before watering on days when watering was due.

4.2.2.7 Trial 2 soil core sampling

As part of Trial 3, soil cores were collected from each pot on 8 November 2024, 11 December 2024, 6 January 2025 and 12 February 2025. Because Trials 2 and 3 shared Control and one vermicast treatment, all Trial 2 treatments were also cored. A custom made 15 mm x 200 mm soil corer (less than the depth of the pots 220 mm) was used to collect the cores. Cores were air-dried in aluminium foil trays before storage in 50 mL centrifuge tubes.

4.2.2.8 Trial 2 bulb size measurements

Approximate bulb size of each onion was measured in mm with a dividing head and ruler with 1 mm graduations on 20/12/2024, 28/12/2024, 31/12/2024, 6/01/2025, 22/01/2025, 30/01/2025, 5/02/2025, 12/02/2025 and 19/02/2025. As the onions were not perfectly round, and on later measuring dates, there was less room to manoeuvre the dividing head measurements were only a guide until the final measurement taken after harvest.

4.2.2.9 Trial 2 harvest

When the leaves had folded (by 26 February 2025), the roots were cut at the base of the onions with scissors. The onions were left to dry until 26 March 2025. The same harvest method as in Section 4.2.1.8 was followed, however, digital callipers rather than sizing rings were used to measure onion bulb size to the nearest mm laterally across the widest point.

4.2.2.10 Trial 2 vermicast and soil analyses

Trial 2 vermicast and soil analyses were conducted in the same manner as Trial 1. Refer to Section 4.2.1.9.

4.2.2.11 Trial 2 statistical analyses

The time to final emergence (days taken for all viable seeds to emerge) and the number of viable seeds were analysed using Kruskal-Wallis tests as data normalcy and assumptions of homogenous variance were not met. Kruskal-Wallis was also used for analyses of onion mass, bulb diameter, yield and root DM.

Root dry matter was compared between Trials 1 and 2 using a two-sample Student's t-test restricted to treatments common to both trials (Control, 0I, 0B, 1B, 2B).

4.2.3 Trial 3: 2024-2025 phosphorus supplementation trial

As stated in Section 4.1, Trial 2 (2024-2025 timing trial) and Trial 3 (phosphorus (P) supplementation) were run concurrently using a low Olsen P soil. The same three pots served as the Control in both trials. These are labelled as "Control" in both trials. Another three pots served as a treatment in both trials. This was the vermicast broadcast (surface applied) at sowing (0BX) treatment in Trial 2 and the vermicast + 100% P fertiliser (VP100 X) treatment in Trial 3.

As the trials were run concurrently, the methods for Trial 3 were almost the same as Trial 2. Rather than repeating all details, this methods section will refer the reader back to relevant sections under Section 4.2.2, with variations such as fertiliser regimes clearly stated.

Table 4-5: Nutrient content of fertilisers used in Trial 2 (2024-2025 timing trial). Nutrient content is reported as percent weight of element by product weight. N = nitrogen, P = phosphorus, K = potassium, S = sulphur, Mg = magnesium, Ca = calcium.

Fertiliser	Source	N	P	K	S	Mg	Ca
Diammonium Phosphate Cropmaster (DAP)	Ravensdown	18	20		1		
SustaiN (urea)	Ballance®	46					
Muriate of Potash (MOP)	Ballance®			50			
Calmag (granulated magnesium)	Ballance®					38	2
SQM Qrop	Sociedad Química y Minera	14		11			12

Table 4-6: Base fertiliser rates for Trial 2 (2024-2025 timing trial). Base fertiliser was applied on 03/09/2024, two weeks before onions were sown. Refer to Table 4-5 for fertiliser nutrient contents. Pot area used in calculations was 0.038 m^2. N = nitrogen, K = potassium, Mg = magnesium, Ca = calcium, S = sulphur.

MOP				Calmag						DAP							
Fertiliser		K applied		Fertiliser		Mg applied		Ca applied		Fertiliser		P applied		N applied		S applied	
kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot
280	1.06	140.0	0.53	260	0.99	98.8	0.38	4.4	0.02	500	1.90	100.0	0.38	88.0	0.33	5.0	0.02

Table 4-7: Side dressing fertiliser rates for Trial 2 (2024-2025 timing trial) and Trial 3 (P supplementation trial). The first side dressing was applied at the 1-2 leaf stage, the second seven weeks later and the final one four weeks later. Refer to Table 4-5 for fertiliser nutrient contents. Pot area used in calculations was 0.038 m^2. N = nitrogen, K = potassium, Ca = calcium.

Date	SustaiN				SQM							
	Fertiliser		N applied		Fertiliser		N applied		K applied		Ca applied	
	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot
23/10/2024	109	0.41	50.0	0.19								
13/12/2024					250	0.95	35	0.13	27.5	0.10	30	0.11
09/01/2024					200	0.76	28	0.11	22	0.08	24	0.09

Trial 3 was designed as a P sparing trial both with and without vermicast broadcast at sowing. The Control received 100% of the P recommended to grow an onion crop on a low Olsen P soil. Phosphorus was applied as diammonium phosphate (DAP) fertiliser. The P sparing treatments were 75%, 50%, 25% and 0% of the recommended rate of DAP. Vermicast treatments were applied and compared to a non-vermicast control. The treatments are reported in Table 4-9 and depicted in Figure 4-3.

Table 4-8: Treatments for 2024-2025 phosphorus (P) supplementation trial. Treatments with "V" mean vermicast was applied at sowing. The numbers following the "P" state the percentage of recommended P fertiliser applied to the pot. See Figure 4-3 for diagrammatic representation.

Treatment	Description
P0 X	No P applied
P25 X	25% recommended P applied
P50 X	50% recommended P applied
P75X	75% recommended P applied
P100 X (Control)	100% recommended P applied
VP0 X	12.5 t FM/ha broadcast at sowing, no P applied
VP25 X	12.5 t FM/ha broadcast at sowing + 25% recommended P applied
VP50 X	12.5 t FM/ha broadcast at sowing + 50% recommended P applied
VP75 X	12.5 t FM/ha broadcast at sowing + 75% recommended P applied
VP100 X	12.5 t FM/ha broadcast at sowing + 100% recommended P applied

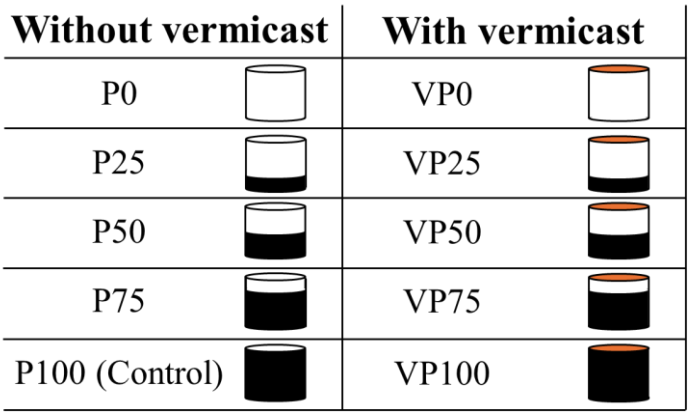


Figure 4-3: Representation of treatment applications. Pots are represented by cylinders. Vermicast application (V) is represented by the orange colour at the top of the cylinder. The proportion of recommended phosphorus (P) applied is expressed as the proportion of the cylinder coloured black. See Table 4-8 for treatment details.

4.2.3.1 Trial 3 set up and onion sowing

Trial 3 was set up at the same time as Trial 2, so much of the following section is detailed under Section 4.2.2.1. The same batches of seeds and soil used in Trial 2 were used in Trial 3. The Trial was carried out in the same glasshouse as Trial 2. Other than vermicast and P fertiliser applied prior to the trial starting, all experimental units were treated the same, including watering volumes and frequency. Each treatment was

replicated three times. In total ten experimental units (pots) were set up. Four dummy pots were also set up (counted under Trial 2).

Each pot was fertilised at a rate of 280 kg Muriate of Potash (MOP)/ha and 260 kg Calmag/ha (

Table 4-10). The Diammonium Phosphate (DAP; phosphorus) base fertiliser application varied between treatments. For treatments P100 (Control) and VP100, DAP fertiliser was applied at 100% of the recommended rate (500 kg/ha). For treatments P0, P25, P50, P75, VP0, VP25, VP50, VP75, DAP application was applied as specified in Table 4-11. As DAP contains N, pots receiving less DAP than the Control and VP100 treatments, also received less N from the DAP. To balance N between all treatments, the equivalent not supplied by DAP was provided by SustaiN. All pots received a total of 0.33 g N per pot, derived from one or both of DAP Cropmaster or SustaiN, depending on the treatment. The fertilisers were mixed into the soil.

Each pot received 500 mL water, the equivalent of 13.2 mm rainfall and were rewatered again with 500 mL each on 9 September 2024.

The trial began on 18 September 2024. The soil in each pot was remixed by hand in a separate container and returned to its original pot. Twelve onion seeds were sown in each pot (six pairs of two) at 2 mm depth, with 250 mL soil spread over the top. Vermicast was applied at a rate of 12.5 t/ha (47.5 g/pot) to the VP treatments. All pots were misted with water.

Each pot was placed in a saucer and placed randomly around the outside edges of three moveable tables.

For watering, maintenance, pest and disease prevention, soil core sampling, fertiliser side dressings, bulb size measurements, harvest, and vermicast and soil analyses refer to the relevant sections under Section 4.2.2.3.

4.2.3.2 Trial 3 soil Olsen P testing

A standard Olsen P extraction method from Lincoln University was used to test the final soil core samples. This method follows the ISO 11263 method[5] and uses activated carbon to absorb any coloured soluble organic matter or organic P that could interfere with the development of the molybdenum blue coloured complex for

[5] ISO 11263:1994: Determination of phosphorus. https://www.iso.org/standard/19241.html. Phosphorus levels are determined via the reaction of ortho-phosphate with molybdenum and antimony in an acid medium to form a phosphor-antimony /molybdenum complex, which is reduced with ascorbic acid to form a blue colour; the absorbance is measured at 880 nm. (Adopted from Murphy & Riley method).

determining the final P. The original methods are detailed in Olsen *et al.* (1954) and Murphy and Riley (1962).

A 1 g ± 0.05 g subsample of air-dry, <2 mm sieved soil and 0.2 g activated carbon were weighed into a 50 mL falcon tube (centrifuge tube). A fresh extractant of 0.5 M sodium hydrogen carbonate ($NaHCO_3$) (with 1 mL 0.2% Superfloc/L) was adjusted to pH 8.5 dropwise with 6 M NaOH. Three blanks were included. Twenty millilitres of extractant was added to each tube before shaking on an end over end shaker for 30 minutes. Samples were centrifuged at 2000 rpm for 10 minutes before immediate filtering through Whatman Number 42 filter paper into 30 mL vials. Samples were frozen before sending to Lincoln University for analysis on a SMARTCHEM 200 (AMS, Frepillon, France) fully automated, direct read, bench top, discrete analyser. The applicable range is from the minimum detection limit 0.020 to 1.200 mg P/L.

Olsen P content is normally calculated by:

$$P\ (\mu g/g\ ) = \frac{\mu g/mL - blank\ x\ 20}{soil\ weight}$$

however, the blank values returned were greater than the soil Olsen P values. Olsen P was calculated without removing the blank values and are used as comparative values only for this study.

4.2.3.3 Soil allophane testing

Allophane presence was measured using the sodium fluoride (NaF) (Fieldes & Perrott) test. An aggregate (about 10 mg) of soil was placed on filter paper (treated with phenolphthalein indicator and dried before testing). A drop of saturated aqueous NaF solution (1 M NaF, maintained in presence of undissolved NaF) was applied to the aggregate and the reaction (indicated by appearance of a red colour on the indicator paper within a specified time period) observed (Fieldes & Perrott, 1966).

4.2.3.4 Trial 3 statistical analysis

Homogeneity of variance was assessed using Levene's test and normality was evaluated by examining ANOVA diagnostic plots. Shapiro-Wilk testing was not performed due to small sample sizes (n = 3 per treatment). Analysis of variance (ANOVA) was used for analysis of soil Olsen P after checking for homogeneity of variance using Levene's test. Where ANOVA indicated significant treatment effects ($p < 0.05$), means were compared using Fisher's LSD test with Bonferroni adjustment. Kruskal-Wallis was used for analyses of onion mass, bulb diameter, yield and root DM.

Small and medium onion counts per pot were compared across trials using Kruskal-Wallis tests. Treatments were pooled within each trial. Dunn's post-hoc test with Bonferroni adjustment was applied where significant differences were detected ($p < 0.05$). As treatments differed between trials (except for Control/P100 and 0B/VP100 in Trials 2 and 3), this comparison should be treated as exploratory, not definitive.

Soil Olsen P was analysed using a one-way ANOVA with treatment as the fixed factor. Homogeneity of variance was assessed using Levene's test. Fisher's Least Significant Difference test with Bonferroni adjustment was applied following a significant ANOVA result ($p < 0.05$).

Table 4-9: Nutrient content of fertilisers used in Trial 3 (2024-2025 P supplementation trial). Nutrient contents collected from product Safety Data Sheets is reported as percent weight of element by product weight. N = nitrogen, P = phosphorus, K = potassium, S = sulphur, Mg = magnesium, Ca = calcium.

Fertiliser	Source	N	P	K	S	Mg	Ca
Diammonium Phosphate Cropmaster (DAP)	Ravensdown	18	20		1		
SustaiN (urea)	Ballance®	46					
Muriate of Potash (MOP)	Ballance®			50			
Calmag (granulated magnesium)	Ballance®					38	2
SQM Qrop	Sociedad Química y Minera	14		11			12

Table 4-10: Base fertiliser rates for Trial 3 (P supplementation trial). Base fertiliser was applied on 03/09/2024, two weeks before onions were sown. Refer to Table 4-9 for fertiliser nutrient contents. Pot area used in calculations was 0.038 m^2. N = nitrogen, K = potassium, Mg = magnesium, Ca = calcium.

MOP				Calmag					
Fertiliser		K applied		Fertiliser		Mg applied		Ca applied	
kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot
280	1.06	140.0	0.53	260	0.99	98.8	0.38	4.4	0.02

Table 4-11: Treatment fertiliser rates for Trial 3 (P supplementation trial). Treatment fertilisers were applied with base fertiliser on 03/09/2024, two weeks before onions were sown. Refer to Table 4-9 for fertiliser nutrient contents. Pot area used in calculations was 0.038 m^2. N = nitrogen, P = phosphorus, K = potassium, Mg = magnesium, Ca = calcium, S = sulphur.

		DAP								SustaiN				Total N
		Fertiliser		P applied		N applied		S applied		Fertiliser		N applied		
Treatment	P requirements	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	g/pot
P0 & VP0	0%	0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	191.7	0.73	88.0	0.33	0.33
P25 & VP25	25%	125	0.48	25.0	0.10	22.0	0.08	1.3	0.00	143.8	0.55	66.0	0.25	0.33
P50 & VP50	50%	250	0.95	50.0	0.19	44.0	0.17	2.5	0.01	95.9	0.36	44.0	0.17	0.33
P75 & VP75	75%	375	1.43	75.0	0.29	66.0	0.25	3.8	0.01	47.9	0.18	22.0	0.08	0.33
P100 & VP100	100%	500	1.90	100.0	0.38	88.0	0.33	5.0	0.02	0.0	0.00	0.0	0.00	0.33

Table 4-12: Side dressing fertiliser rates for Trial 3 (2024-2025 P supplementation trial). The first side dressing was applied at the 1-2 leaf stage, the second seven weeks later and the final one four weeks later. Refer to Table 4-9 for fertiliser nutrient contents. Pot area used in calculations was 0.038 m^2. N = nitrogen, K = potassium, Ca = calcium.

Date	SustaiN				SQM							
	Fertiliser		N applied		Fertiliser		N applied		K applied		Ca applied	
	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot	kg/ha	g/pot
23/10/2024	109	0.41	50.0	0.19								
13/12/2024					250	0.95	35	0.13	32.5	0.12	30	0.11
09/01/2024					200	0.76	28	0.11	22	0.08	24	0.09

4.3 Results

4.3.1 Trial 1: 2023-2024 timing of vermicast application trial

4.3.1.1 Trial 1 soil and vermicast nutrients

Soil and vermicast nutrients and heavy metals are reported in Table 4-13 and Table 4-14. The soil had a relatively high Al content, which is unsurprising given its allophane content (the soil was classed as a Typic Orthic Allophanic soil, and allophane was detected in the soil profile – see Section 5.5.1). The vermicast had a high Ca content, which could be from the pulp and paper mill solids component of the vermicast used (calcium is used in pulp manufacturing see Section 3.4.1.4 regarding Ca and S use in cardboard manufacturing).

Table 4-13: Nutrient analysis for first season glasshouse trial soil and vermicast. *Italicised* results are below quantitation limits.

Nutrient	Soil	Vermicast	Vermicast nutrient application rate	
	% DM	% DM		
C	4.4	15.0		
N	0.41	0.84		
C:N	10.5	18.0		
	mg/kg DM	mg/kg DM	kg nutrient/ha	g nutrient/pot
N	4,141	8,355	48.5	0.18
P	1,179	3,933	22.8	0.09
K	*372*	*959*	*5.6*	*0.02*
S	*218*	*1,685*	*9.8*	*0.04*
Ca	*2,183*	73,611	*426.9*	1.62
Mg	387	1,080	6.3	0.02
Al	24,049	9,701	56.3	0.21
B	ND	ND	-	-
Co	2.59	*1.40*	0.0	0.00
Fe	9,816	5,289	30.7	0.12
Na	*115*	844	4.9	0.02
Mn	957	236	1.4	0.01

Except for Cadmium, none of the limits for heavy metals were approached or exceeded by the vermicast. Cadmium was detected below quantitation limits in both the soil and the vermicast so these results should be interpreted with caution. This particular concern was discussed in Section 3.4.2.3.5 as Cd was also detected below quantitation limits in other unrelated materials, but also well exceeded the land application limits.

Table 4-14: Heavy metal analysis for first season glasshouse trial soil and vermicast in mg/kg DM, except vermicast application rate. These are compared to the limits for land application of biosolids in New Zealand (New Zealand Water and Wastes Association, 2003; Water New Zealand, 2025). *Italicised* results are below quantitation limits.

Heavy metal	Soil	Vermicast	2003 limit	2025 limit	Vermicast heavy metal kg/ha	application rate g/pot
As	0.44	*0.14*	20	30	*0.00*	*0.00*
Cd	*71*	*101*	3	6.5	*0.59*	*0.00*
Cr	6.03	42	600	1,500	0.24	0.00
Cu	12.2	30	300	750	0.18	0.00
Pb	7.10	7.15	250	300	0.04	0.00
Hg	Not tested	Not tested	2	7.5		-
Ni	3.73	3.87	60	135	0.02	0.00
Zn	11.3	75	600	1,250	0.43	0.00

4.3.1.2 Trial 1 glasshouse conditions

Ambient temperature in the glasshouse was recorded hourly. Ambient temperature inside the glasshouse was maintained at an average of 21.6 °C with a minimum of 6.2 °C recorded on October 6, 2023, and a maximum of 34.5 °C recorded on January 10, 2024 (Figure 4-4). Twenty percent of the hourly recorded temperatures exceeded 27°C throughout the trial duration. Exceedances were recorded on 86% of the trial days (121 out of 178 total). Hourly temperature exceeded 27 °C on five days before mid-October and then most days until the end of the trial i.e. temperatures exceeded the optimal range throughout bulb formation and development.

Average daily radiation sum (total accumulation of solar energy) increased over the trial duration from 368 J/cm^2 on 5 September 2023 to 1,081 J/cm^2 on 29 February 2024. Radiation fluctuated daily, peaking in January (Figure 4-5).

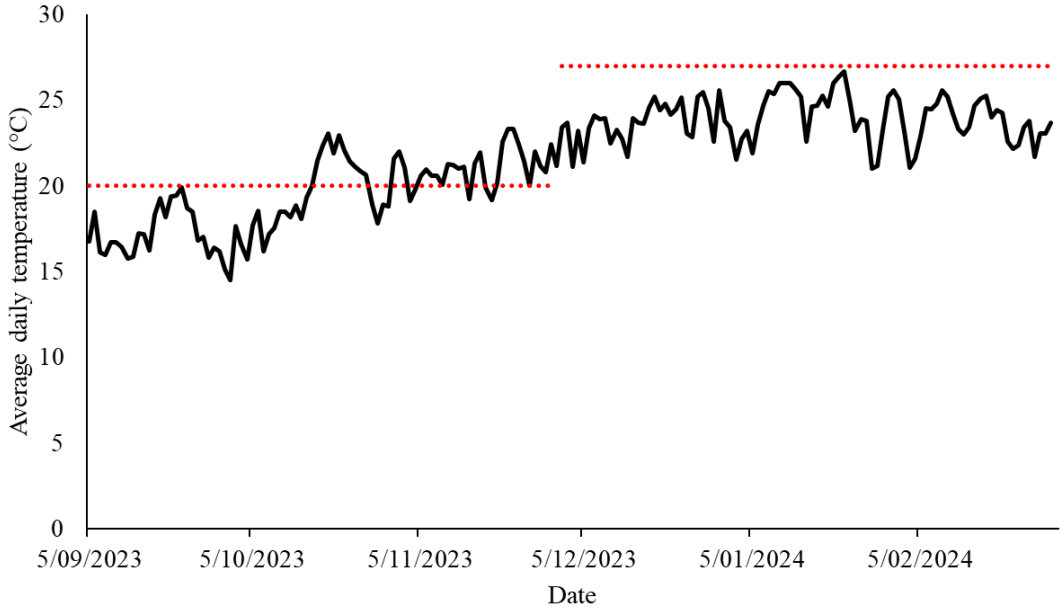


Figure 4-4: Average daily temperature for glasshouse Trial 1 for trial duration. The solid black line is the recorded temperature in the glasshouse. The dotted red line is the maximum optimal temperature for onion growth in early growth (20 °C) to bulb development (27 °C) (Khokhar, 2017). Date of change from early development to bulb development is approximate.

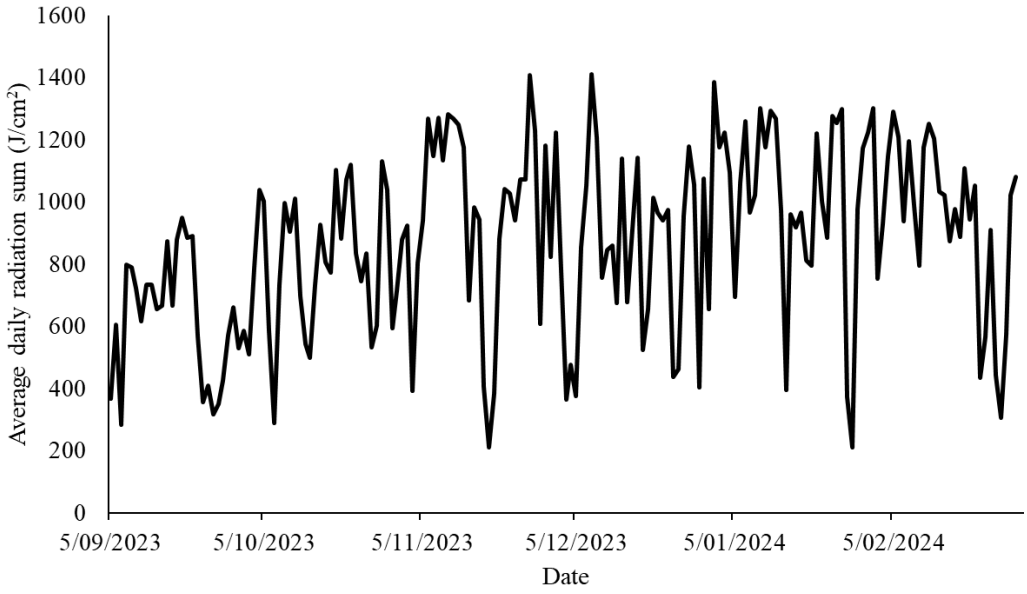


Figure 4-5: Average daily radiation sum for glasshouse Trial 1 for trial duration.

4.3.1.3 Trial 1 seedling emergence

Germination percentage was calculated from the total number of seedlings emerged by Day 12. Both vermicast treatments appeared to speed up emergence and increase the total number of seedlings emerged (viable seeds, see Figure 4-6, Table 4-15). However, the Kruskal-Wallis test returned no significant differences between the Control,

Broadcast or Incorporated vermicast treatments in the number of seedlings emerged, or days taken to reach final emergence (p = 0.469, 0.224; Table 4-15).

Table 4-15: Average number of onion seedlings emerged, germination success and average number of days taken to reach full emergence during emergence trial. Values are ± standard deviation. "Broadcast" is the 12.5 t fresh matter (FM)/ha vermicast rate surface applied at sowing, "Incorporated" is the 12.5 t FM/ha vermicast rate mixed into the soil at sowing. Data for power tests are also included.

Treatment	**Average seedlings emerged**	**Germination (% out of 36)**	**Average days to final emergence**
Control	10.2 ± 1.0	85.4%	11.0 ± 1.2
Incorporated	10.5 ± 1.7	93.8%	9.5 ± 1.0
Broadcast	11.2 ± 1.0	87.5%	10.0 ± 1.6
Kruskal-Wallis p-values	*0.469*		*0.224*
Post hoc power analysis (risk of false negative/Type II error)			
Cohen's f value	0.404		0.593
Total sample size	12		12
Total groups	3		3
Replicates (pots)	4		4
Power at α = 0.05	0.170		0.324
Type II error rate	83%		63%
A priori power analysis (minimum replicates required to achieve power of at least 0.80)			
Minimum replicates	21		11

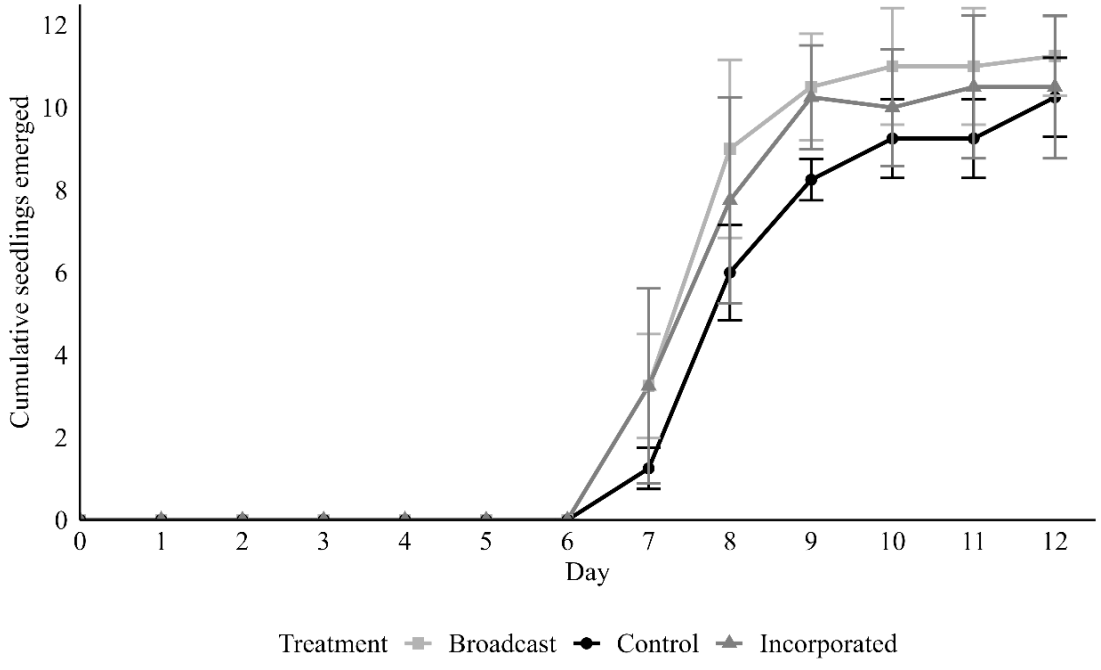


Figure 4-6: Cumulative number of seedlings emerging throughout the trial. Day 0 = day of sowing (5 September 2023). "Broadcast" is the 12.5 t fresh matter (FM)/ha vermicast rate surface applied at sowing, "Incorporated" is the 12.5 t FM/ha vermicast rate mixed into the soil at sowing.

4.3.1.4 Trial 1 onion yield, bulb mass and size

There were no significant differences between treatments for average yield ($p = 0.092$) or individual onion mass ($p = 0.713$). According to the Q-Q plots (not displayed), all data were normally distributed. Levene's test for homogeneity of variance passed ($p = 0.522$). The ANOVAs were confirmed by Kruskal-Wallis ($p = 0.119$ for yield and 0.558 for average individual onion mass). The results are presented in Table 4-16, Figure 4-7 and Figure 4-8.

A post-hoc power test for average bulb mass showed there was a 74% chance of missing a real effect, if one existed. Twelve replicates would have been required to achieve power of at least 0.80. A post-hoc power test for average root DM showed there was a 25% chance of missing a real effect, if one existed. Five replicates would have been required to achieve a power of at least 0.80 (Table 4-16). Although the bulb mass and root DM power analyses show that more replicates were needed to correctly detect significant differences between treatments, the achieved power was higher than for seedling emergence.

Table 4-16: Average onion yield, fresh bulb mass, root dry matter (DM) and number of dead onions at harvest. Error reported is ± standard deviation. Data for power tests are also included.

Treatment	**Average bulb mass (g/onion)**	**Average root mass (g DM/pot)**	**Average yield (g/pot)**	**Mortality**	
				Count	**%**
Control	71.7 ± 2.7	2.6 ± 0.3	411.4 ± 25.5	1	4.2
0I	74.4 ± 10.8	2.4 ± 0.4	424.3 ± 30.2	1	4.2
0B	75.0 ± 4.4	2.3 ± 0.2	449.9 ± 26.4	0	0.0
1B	71.2 ± 4.8	1.9 ± 0.4	427.2 ± 28.8	0	0.0
2B	73.4 ± 5.0	2.5 ± 0.3	420.1 ± 13.1	1	4.2
3B	71.1 ± 3.4	2.5 ± 0.4	426.5 ± 20.6	0	0.0
4B	69.4 ± 2.3	2.4 ± 0.2	416.4 ± 13.8	0	0.0
5B	68.7 ± 6.4	2.6 ± 0.4	393.1 ± 13.7	1	4.2
ANOVA p-values	*0.712*	*0.069*	*0.092*	*0.772*	
Levene's test p-values	*0.522*	*0.676*	*0.767*	*0.772*	
Kruskal-Wallis p-value	*0.558*	*0.322*	*0.119*	*0.729*	
A priori power analysis					
Cohen's f value	0.405	0.731			
Total sample size	32	32			
Total groups	8	8			
Replicates (pots)	4	4			
Power at $\alpha = 0.05$	0.253	0.750			
Type II error rate	74%	25%			
A priori power analysis (minimum replicates required to achieve power of at least 0.80)					
Minimum replicates	12	5			

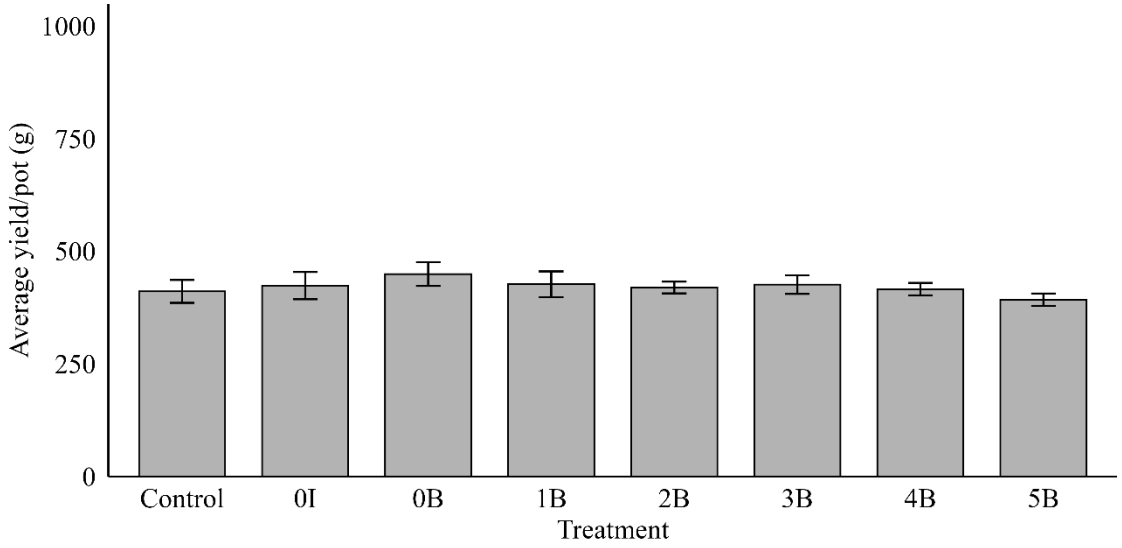


Figure 4-7: Average yield per pot at harvest. Error bars are standard deviation.

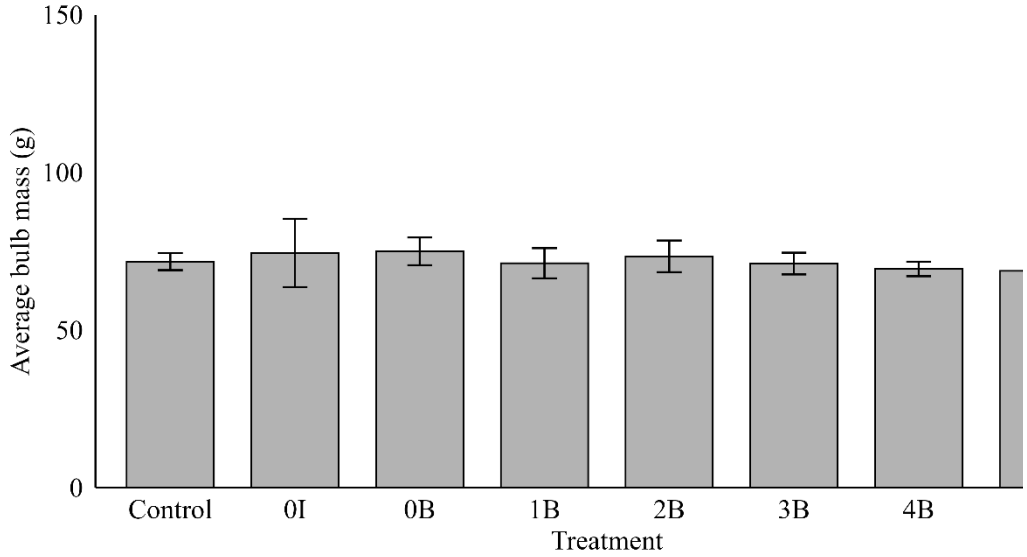


Figure 4-8: Average bulb mass per treatment at harvest. Error bars are standard deviation.

Across the trial, one out of six onions in each of Control 2, 0I1, 2B1 and 5B3 treatments died (Figure 4-9). Treatment had no effect on the likelihood of an onion dying ($p = 0.772$). However, a Wilcoxon rank-sum test showed a highly significant effect of onion density ($p = 7.00 \times 10^{-4}$). The fewer onions there were in a pot i.e. those with an onion that had died, the higher the average individual onion mass, though there were few datapoints (4 dead onions /192 total trial onions sown) to confirm this outcome.

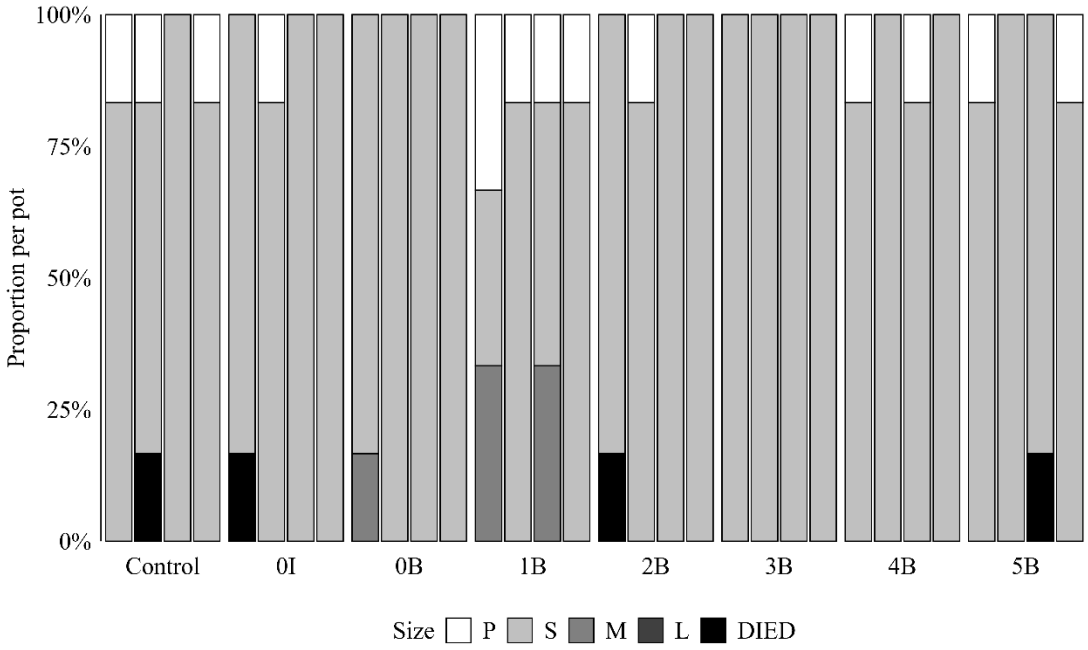


Figure 4-9: Proportion of onions in each size class (P = pickling, S = small, M = medium and L = large), including onions that died during the trial. Replicates (pots) are shown individually for each treatment (n = 6 onions per pot).

No large onions were produced. Only the pickling size class was significant between treatments (0B and 1B, and 1B and 3B, $p = 0.04$). There were no significant differences in other size classes or mortalities (Figure 4-9). Overall, the 1B treatment had the most variability in onion size. It had four medium onions in total. Except for one 0B replicate, no other medium-sized onions were grown.

4.3.1.5 Trial 1 root dry matter production

Neither method of vermicast application nor timing had an effect on root DM production (Table 4-16, Figure 4-10). The ANOVA p-value was close to the significant level of $\alpha = 0.05$ ($p = 0.069$), however, a Kruskal-Wallis test also showed there were no significant differences with $p = 0.322$.

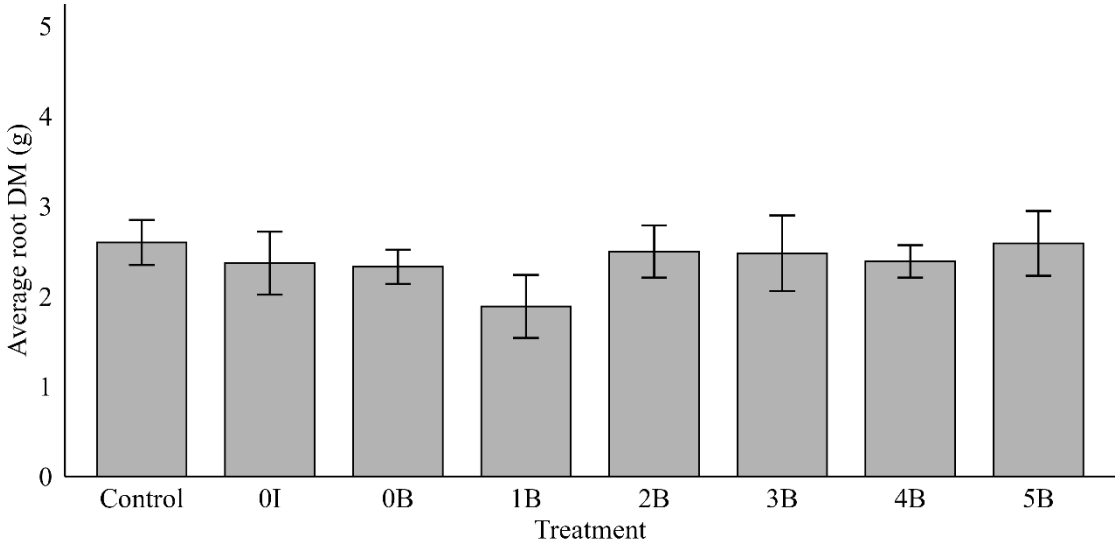


Figure 4-10: Average root dry matter (DM) per treatment. Treatments are the average of four replicates (pots, not onion plants). Error bars are standard deviation.

4.3.2 Trial 2: 2024-2025 timing of vermicast application trial

4.3.2.1 Trial 2 soil and vermicast nutrients

4.3.2.1.1 Initial soil selection

The initial in-house Olsen P screening test on this soil was 11 µg P/g soil which was considered low, making this soil ideal for the P supplementation trial. Initial soil pH prior to the start of the trial averaged at 5.67 which was considered too low for an onion crop. Ten days after liming, another soil sample was tested. The results from the Hill Laboratories testing are reported below and were interpreted using their Technical Note: Soil Tests & Interpretation (Hill Laboratories, n.d.-b). See Table 4-17 for the following paragraph.

The overall pH had increased to 6.5, the Olsen P level remained low (14.7 µg P/g), and Hill Laboratories test results indicated the soil was high in Ca, low in Na and deficient in K and Mg. The cation exchange capacity (CEC) of the soil was 'medium' for an agricultural soil at 21 me/100 g. This is a measure of the soil's ability to hold exchangeable cations (H^+, Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+}). Total base saturation (TBS) is a measure of the total exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) divided by the CEC. The TBS of the soil was high at 86%, indicating that H^+ and Al^{3+} (acidic cations) were less abundant.

Anion storage capacity (ASC) is an indicator of P retention. The trial soil had a high ASC of >98%.

Table 4-17: Soil test results after liming and prior to base fertilisation and trial initiation. Testing done at Hill Laboratories. Results are reported as received (not on DM basis).

Parameter	Value	Units
pH	6.5	
Resin P	10	mg/kg
Olsen P	10	mg/L
	14.7†	*µg P/g*
Total P	1,254	mg/kg
SO_4-S	95	mg/kg
Extractable organic S	16	mg/kg
K	0.18	me/100 g
K	0.9	%BS
K	3	MAF units
Ca	17	me/100g
Ca	82	%BS
Ca	15	MAF units
Mg	0.49	me/100 g
Mg	2.4	%BS
Mg	7	MAF units
Na	0.08	me/100g
Na	0.4	%BS
Na	3	MAF units
Anion storage capacity	>98	%
Cation exchange capacity	21	me/100 g
Total base saturation	86	%
Volume weight‡	0.68	g/L

†The second Olsen P value was calculated using the volume weight.
‡Volume weight is measured on soil dried at 35-38°C and sieved <2 mm. It is used to convert results between volume and mass. It is not the same as bulk density (Hill Laboratories, n.d.-b).

Unsurprisingly, the vermicast tended to be higher in nutrients than the soil. However, Al, Fe and Mn were higher in the (allophanic) soil – a moderate allophane content was detected using the Fields and Perrott test. Both Al (as allophane) and Fe (as ferrihydrite) are found in allophanic soils as minerals or aluminium- or iron-humus complexes, all of which retain P.

The ash contents of the vermicast and the soil were similar at 77.6% and 75.9% respectively, indicating the vermicast may have a low organic matter content while the soil may have a relatively high organic matter content.

As for Trial 1, except for Cd, none of the limits for heavy metals were approached or exceeded by the vermicast. Cadmium was detected below quantitation limits in both the soil and the vermicast so these results should be interpreted with caution.

Final soil Olsen P levels were not significantly different to each other: Kruskal-Wallis p-value = 0.997, data not shown.

Table 4-18: Nutrient analysis for second season glasshouse trial soil and vermicast. *Italicised* results are below quantitation limits.

	Soil	Vermicast	Vermicast nutrient application rate	
	% DM	**% DM**		
C	11.0	15.1		
N	0.75	0.87		
C:N	14.7	17.3		
	mg/kg DM	**mg/kg DM**	**kg nutrient/ha**	**g nutrient/pot**
N	7,499	8,704	50.5	0.18
P	1,110	3,843	22.3	0.08
K	*90*	*846*	*4.9*	*0.02*
S	ND	*1,912*	*11.1*	*0.04*
Ca	3,928	69,272	401	1.53
Mg	364	969	5.62	0.02
Al	36,539	8,578	49.8	0.19
B	ND	ND	-	-
Co	6.08	*1.30*	*0.01*	*0.00*
Fe	20,258	4,956	29	0.11
Na	134	643	3.73	0.01
Mn	651	221	1.28	0.00

Table 4-19: Heavy metal analysis for second season glasshouse trial soil and vermicast in mg/kg DM. These are compared to the limits for land application of biosolids in New Zealand (New Zealand Water and Wastes Association, 2003; Water New Zealand, 2025). *Italicised* results are below quantitation limits.

	Soil	Vermicast	2003 limit	2025 limit	Vermicast heavy metal application rate kg/ha	g/pot
As	8.40	*0.09*	20	30	0.00	0.00
Cd	*0.43*	*95*	3	6.5	0.55	0.00
Cr	12.5	37	600	1,500	0.22	0.00
Cu	27	29	300	750	0.17	0.00
Pb	7.79	6.61	250	300	0.04	0.00
Hg	Not tested	Not tested	2	7.5	-	-
Ni	*0.77*	4.11	60	135	0.02	0.00
Zn	*16.6*	70	600	1,250	0.41	0.00

4.3.2.2 Trial 2 glasshouse conditions

Ambient temperature inside the glasshouse was maintained at an average of 19.8 °C with a minimum of 5.9 °C recorded on September 18, 2024 and a maximum of 31.5°C recorded on February 2, 2025. Six percent of the hourly recorded temperatures exceeded 27°C throughout the trial duration. Exceedances were recorded on 61% of the trial days (63 out of 103 total). Hourly temperature exceeded 27 °C on five individual

days before December and then most days until the end of the trial i.e. temperatures exceeded the optimal range throughout bulb formation and development.

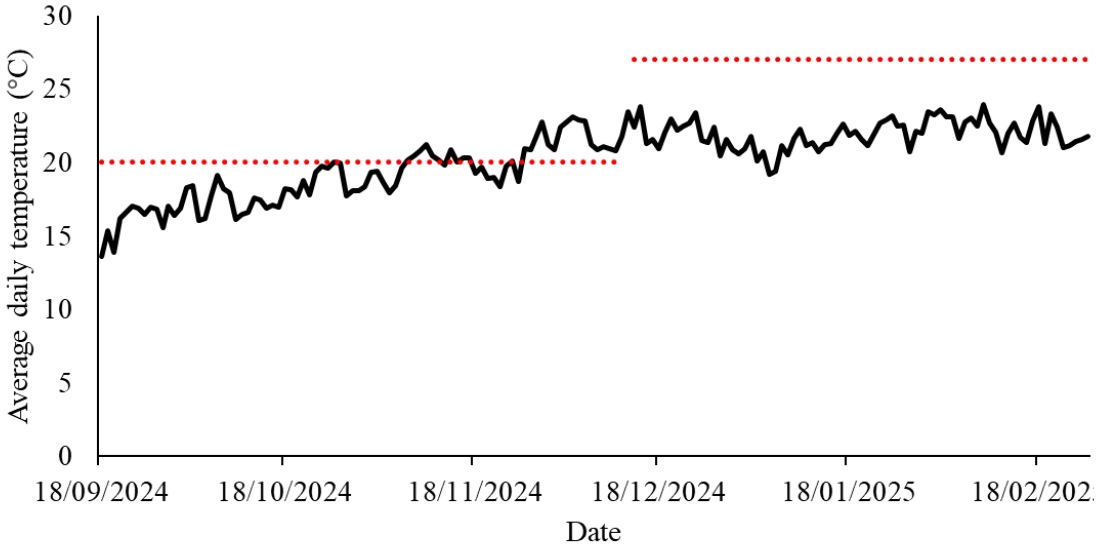


Figure 4-11: Average daily temperature for glasshouse Trials 2 & 3 for trial duration. The solid black line is the recorded temperature in the glasshouse. The dotted red line is the maximum optimal temperature for onion growth in early growth (20 °C) to bulb development (27 °C) (Khokhar, 2017). Date of change from early development to bulb development is approximate.

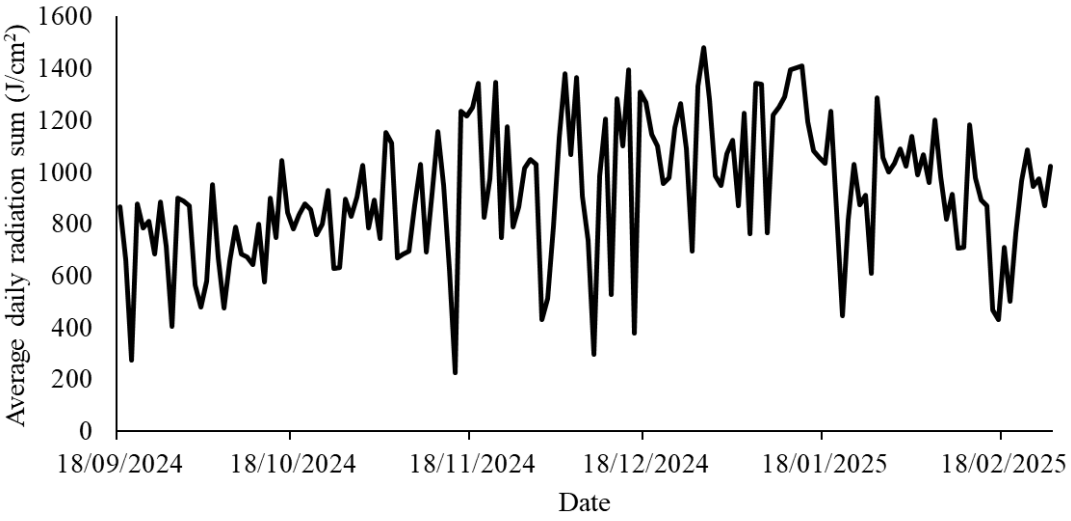


Figure 4-12: Average daily radiation sum for glasshouse Trials 2 & 3 for trial duration.

4.3.2.3 Trial 2 seedling emergence

Germination percentage was calculated from the total number of seedlings emerged by Day 14. Both vermicast treatments appeared to speed up emergence and increase the total number of seedlings emerged (viable seeds, see Figure 4-13, Table 4-20).

However, the Kruskal-Wallis test returned no significant differences between the Control, Broadcast or Incorporated vermicast treatments in the number of seedlings emerged, or days taken to reach final emergence (p = 0.954, ; Table 4-20).

Table 4-20: Average number of onion seedlings emerged, and average number of days taken to reach full emergence during emergence trial. Values are ± standar deviation. "Broadcast" is the 12.5 t fresh matter (FM)/ha vermicast rate surface applied at sowing, "Incorporated" is the 12.5 t FM/ha vermicast rate mixed into the soil at sowing. Data for power tests are also included.

Treatment	**Average seedlings emerged**	**Germination (% out of 36)**	**Average days to final emergence**
Control	10.3 ± 1.2	86.1%	13.0 ± 0.0
Incorporated	10.7 ± 0.6	88.9%	13.0 ± 0.1
Broadcast	10.7 ± 0.6	88.9%	12.3 ± 0.6
Kruskal-Wallis p-value	*0.954*		*0.348*
Post hoc power analysis (risk of false negative/Type II error)			
Cohen's f value	0.283		0.606
Total sample size	9		9
Total groups	3		3
Replicates (pots)	3		3
Power at α = 0.05	0.086		0.228
Type II error rate	91%		77%
A priori power analysis (minimum replicates required to achieve power of at least 0.80)			
Minimum replicates	42		10

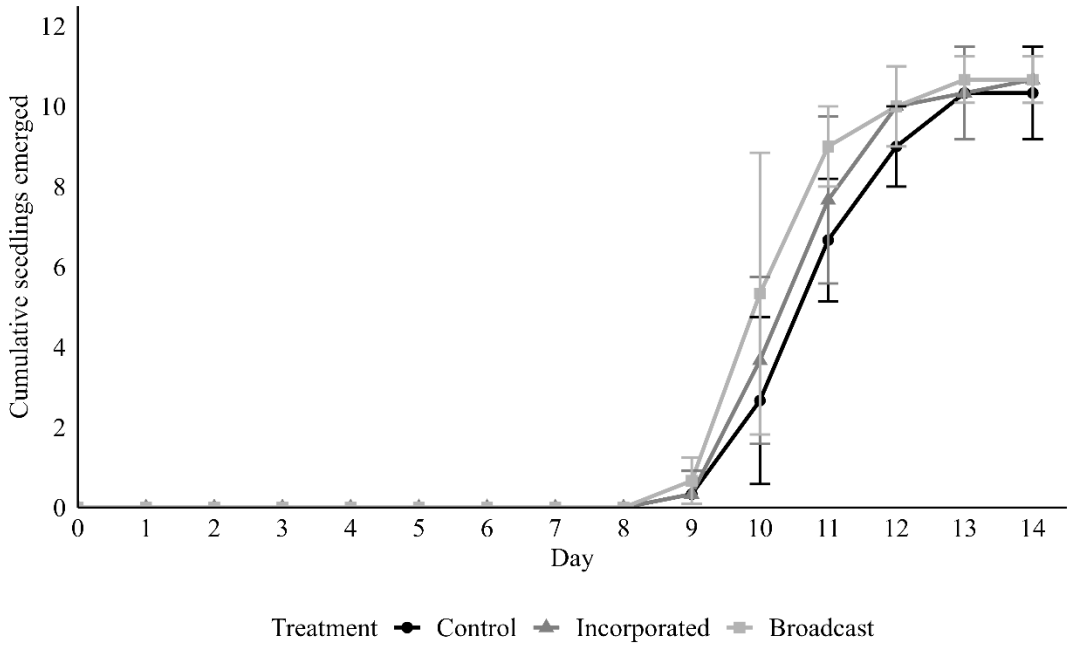


Figure 4-13: Cumulative number of seedlings emerging throughout the trial. Day 0 = day of sowing (18 September 2024). "Broadcast" is the 12.5 t fresh matter (FM)/ha vermicast rate surface applied at sowing, "Incorporated" is the 12.5 t FM/ha vermicast rate mixed into the soil at sowing.

A post-hoc power test for average number of seedlings emerged showed there was a 91% chance of missing a real effect if one existed. Forty-two replicates would have

been required to achieve power of at least 0.80. A post-hoc power test for average days to final emergence showed there was a 77% chance of missing a real effect, if one existed. Ten replicates would have been required to achieve a power of at least 0.80 Table 4-20.

4.3.2.4 Trial 2 onion yield, bulb mass and size

There were no significant differences between treatments for average yield ($p = 0.434$), individual onion mass ($p = 0.434$) or bulb diameter ($p = 0.286$). The results are presented in Table 4-16 and Figure 4-14 – Figure 4-16.

A post-hoc power test for average bulb mass there was an 81% chance of missing a real effect, if one existed. Twelve replicates would have been required to achieve power of at least 0.80. A post-hoc power test for average bulb diameter showed there was a 54% chance of missing a real effect, if one existed. Five replicates would have been required to achieve a power of at least 0.80. A post-hoc power test for average root DM showed there was an 88% chance of missing a real effect, if one existed. Twenty replicates would have been required to achieve a power of at least 0.80 (Table 4-21).

Most onions were in the medium size class, with the remainder in the small size class. There were no significant differences between treatments for number of small ($p = 0.453$) or medium onions ($p = 0.453$). There were no pickling or large onions in this trial.

Table 4-21: Average onion yield, fresh bulb mass root dry matter (DM) at harvest. Error reported is ± standard deviation. Data for power tests are also included.

Treatment	**Average bulb mass (g/onion)**	**Average bulb diameter (mm/onion)**	**Average root mass (g DM/pot)**	**Average yield (g/pot)**
Control	130 ± 7.6	61.7 ± 1.5	2.5 ± 0.7	779.6 ± 45.5
0I	132 ± 2.6	62.7 ± 0.0[†]	2.2 ± 0.4	792.6 ± 15.4
0B	126 ± 1.4	60.9 ± 0.3	2.0 ± 0.3	757.3 ± 8.6
1B	133 ± 2.9	62.9 ± 0.4	2.4 ± 0.4	800.1 ± 17.3
2B	129 ± 9.6	62.2 ± 1.6	2.4 ± 0.7	776.0 ± 57.5
Kruskal-Wallis p-value	*0.434*	*0.286*	*0.737*	*0.434*
Post hoc power analysis (risk of false negative/Type II error)				
Cohen's f value	0.476	0.782	0.363	
Total sample size	15	15	15	
Total groups	5	5	5	
Replicates (pots)	3	3	3	
Power at $\alpha = 0.05$	0.187	0.461	0.124	
Type II error rate	81%	54%	88%	
A priori power analysis (minimum replicates required to achieve power of at least 0.80)				
Minimum replicates	12	5	20	

[†]N.B. the 0.0 mm standard deviation for 0I is correct. All three replicate means were 62.7 mm.

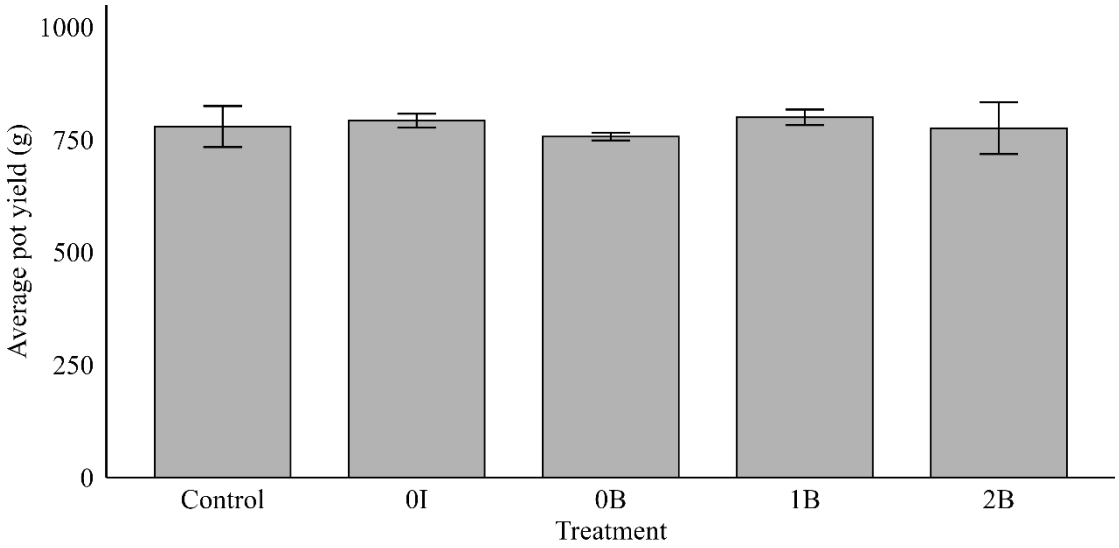


Figure 4-14: Average treatment yield per pot at harvest. Error bars are standard deviation.

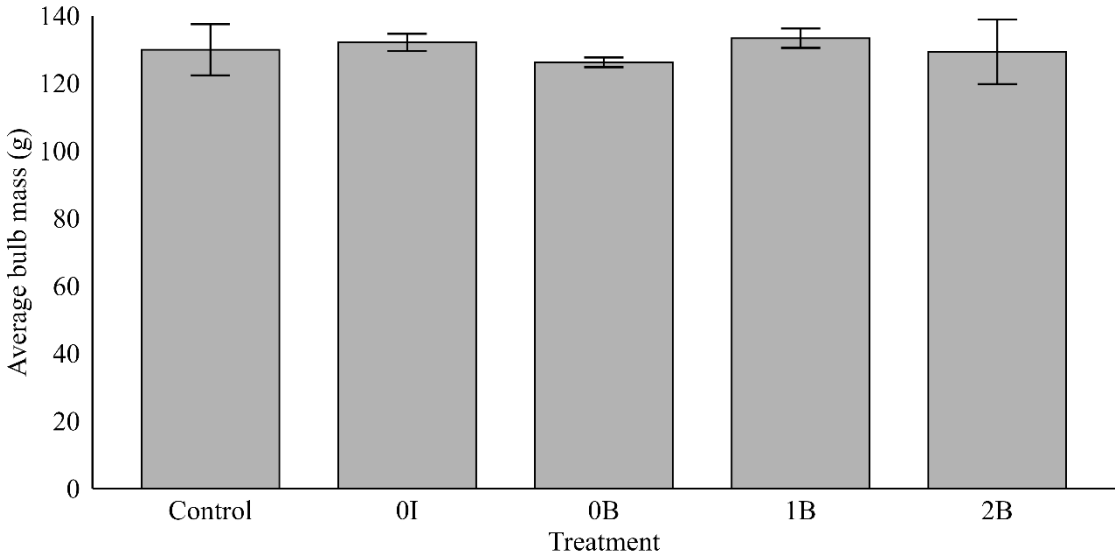


Figure 4-15: Average bulb mass per treatment at harvest. Error bars are standard deviation.

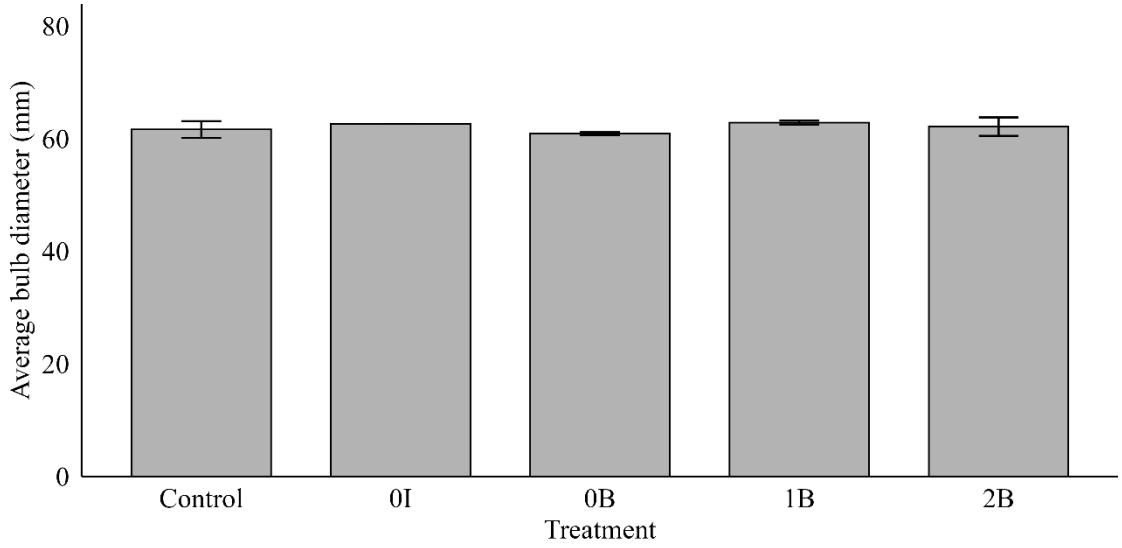


Figure 4-16: Average onion bulb diameter per treatment at harvest. Error bars are standard deviation. N.B. the 0.0 mm standard deviation for 0I is correct. All three replicate means were 62.7 mm.

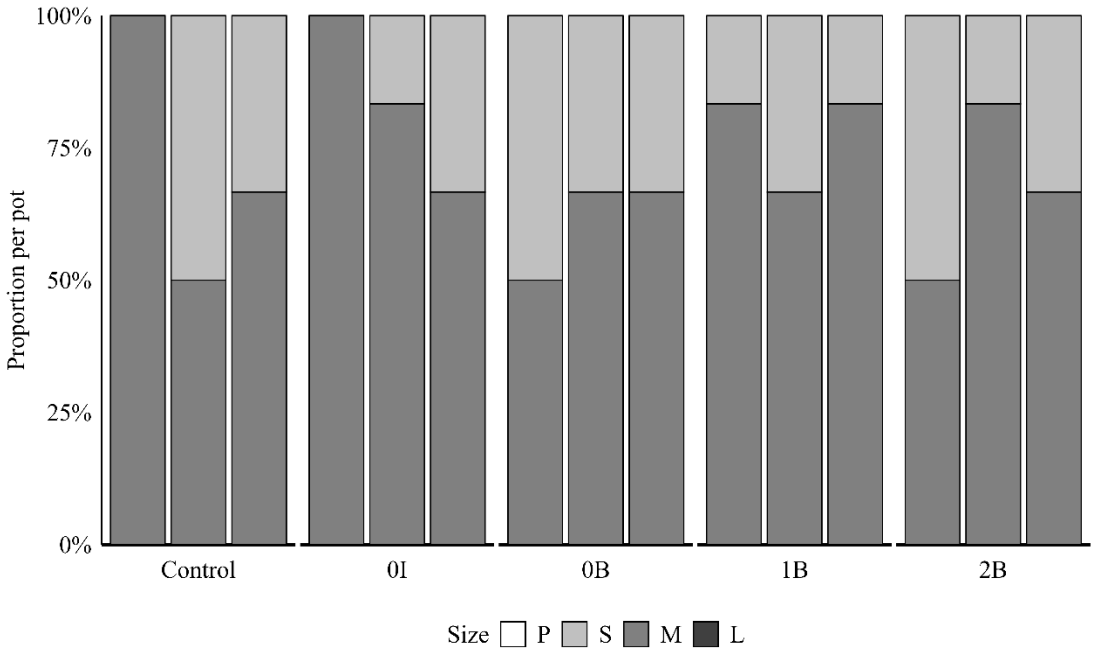


Figure 4-17: Proportion of onions in each size class (P = pickling, S = small, M = medium and L = large), including onions that died during the trial. Replicates (pots) are shown individually for each treatment (n = 6 onions per pot).

4.3.2.5 Trial 2 root dry matter production

Neither method of vermicast application nor timing had an effect on root DM production (Table 4-21, Figure 4-18). A Kruskal-Wallis test showed there were no significant differences with p = 0.737.

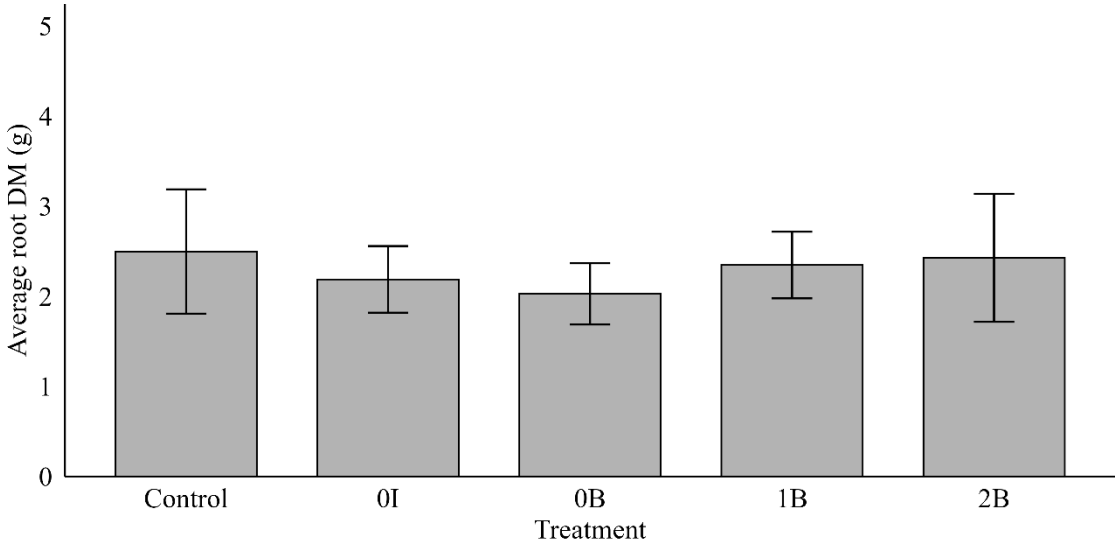


Figure 4-18: Average root dry matter (DM) per treatment. Treatments are the average of three replicates (pots, not onion plants). Error bars are standard deviation.

4.3.2.6 Comparison of root dry matter production, Trials 1 and 2

Given that root DM production appeared the same between Trials 1 and 2, despite larger onions, and almost double the onion mass and yield in Trial 2, an additional test was conducted. Average root DM for Trial 1 was 2.3 ± 0.4 g DM and 2.3 ± 0.5 g DM for Trial 2. Levene's test for homogeneity of varience passed ($p = 0.435$) and Student's t-test showed there was no significant difference between the two trials ($p = 0.803$).

4.3.3 Trial 3: 2024-2025 phosphorus supplementation trial

4.3.3.1 Trial 3: soil and vermicast nutrients

Trial 3 shared the same soil and analysis methods as Trial 2. See Sections 4.3.2.1 and 4.3.2.1.1 (Trial 2) for results regarding soil and vermicast nutrients.

4.3.3.1.1 Trial 3 soil Olsen P at harvest

Final Olsen P content was significantly lower in P0 (no vermicast, no DAP fertiliser) than the three treatments P100 (Control), VP100 (vermicast + 100% DAP) and VP75 (vermicast + 75% DAP) (Table 4-22 and Figure 4-19). The VP75 treatment also had significantly higher final Olsen P than the P50 treatment.

A post hoc power analysis for average final soil Olsen P returned an achieved power of 0.992, indicating that the risk of a Type II error (false negative) was very low (0.8%; Table 4-22).

Table 4-22: Final soil Olsen P levels. Note that these results are not absolute. They are for comparative purposes only. Significant differences between treatments are indicated by letters a-c. See Section 4.2.3.2 in the methods and Table 4-17 in the results. Data for power tests are also included.

Treatment	Olsen P	Significance
P100 (Control)	14.3 ± 0.4	ab
P75	12.8 ± 1.5	abc
P50	11.7 ± 1.1	bc
P25	12.6 ± 1.4	abc
P0	10.3 ± 1.2	c
VP100	14.7 ± 2.2	ab
VP75	15.6 ± 1.0	a
VP50	12.3 ± 1.0	abc
VP25	12.2 ± 0.9	abc
VP0	12.3 ± 0.7	abc
Levene's test p-value	*0.982*	
ANOVA p-value	*0.002*	
Post hoc power analysis (risk of false negative/Type II error)		
Cohen's f value	1.267	
Total sample size	30	
Total groups	10	
Replicates (pots)		
Power at α = 0.05	0.992	
Type II error rate	0.8%	

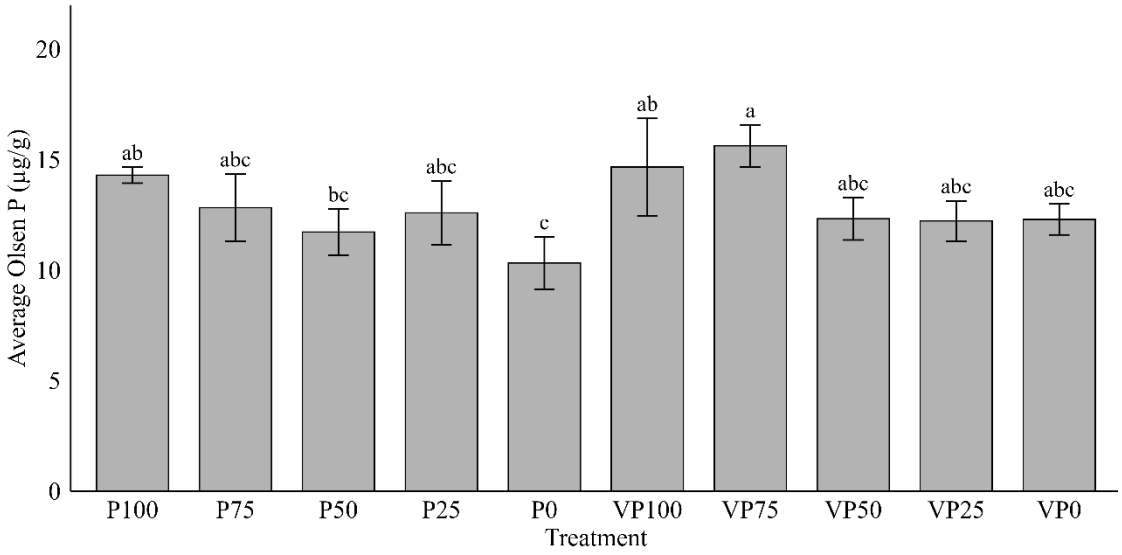


Figure 4-19: Final soil Olsen P content. Significant differences between treatments are indicated by letters a-c. Note that these results are not absolute. They are for comparative purposes only. See Section 4.2.3.2 in the methods and Table 4-17 in the results.

4.3.3.2 Trial 3 glasshouse conditions

As Trial 3 was conducted at the same time as Trial 2, Section 4.3.2.2 (Trial 2) reports the results regarding glasshouse conditions for Trial 3.

4.3.3.3 Trial 3 onion yield, bulb mass and size

There were no significant differences between treatments for average yield or individual onion mass (both p = 0.463). There were also no differences in bulb diameter (p = 0.269) or root mass (p = 0.310). The results are presented in Table 4-23 and Figure 4-20 – Figure 4-22.

A post-hoc power test for average bulb mass there was a 58% chance of missing a real effect if one existed. Six replicates would have been required to achieve power of at least 0.80. A post-hoc power test for average bulb diameter showed there was a 42% chance of missing a real effect, if one existed. Five replicates would have been required to achieve a power of at least 0.80. A post-hoc power test for average root DM showed there was a 46% chance of missing a real effect, if one existed. Five replicates would have been required to achieve a power of at least 0.80 (Table 4-23).

Table 4-23: Average onion yield, fresh bulb mass, root dry matter (DM) and number of dead onions at harvest. Error reported is ± standard deviation. Data for power tests are also included.

Treatment	**Average bulb mass (g/onion)**	**Average bulb diameter (mm/onion)**	**Average root mass (g DM/pot)**	**Average yield (g/pot)**	**Mortality**	
					Count	**%**
P100 (Control)	129.9 ± 7.6	61.7 ± 1.5	2.5 ± 0.7	779.6 ± 45.5	0	0.0
P75	128.7 ± 4.5	62.2 ± 1.0	2.5 ± 0.3	772.2 ± 26.8	0	0.0
P50	123.9 ± 5.5	60.5 ± 1.8	2.7 ± 0.7	743.2 ± 32.8	0	0.0
P25	125.1 ± 5.0	58.0 ± 4.0	2.9 ± 0.3	750.3 ± 29.8	1	5.6
P0	121.7 ± 6.1	59.9 ± 1.7	3.3 ± 1.0	730.0 ± 36.5	0	0.0
VP100	126.2 ± 1.4	60.9 ± 0.3	2.0 ± 0.3	757.3 ± 8.6	0	0.0
VP75	129.2 ± 11.3	61.6 ± 1.3	2.4 ± 0.5	775.0 ± 67.6	0	0.0
VP50	125.2 ± 2.2	60.8 ± 0.8	2.6 ± 0.4	751.3 ± 13.1	0	0.0
VP25	125.3 ± 3.0	60.9 ± 1.0	3.0 ± 0.5	752.0 ± 18.1	0	0.0
VP0	118.8 ± 5.0	59.6 ± 0.9	2.5 ± 0.3	712.5 ± 30.1	0	0.0
Kruskal-Wallis p-value	*0.463*	*0.269*	*0.310*	*0.463*		
Post hoc power analysis (risk of false negative/Type II error)						
Cohen's f value	0.594	0.709	0.628			
Total sample size	30	30	30			
Total groups	10	10	10			
Replicates (pots)	3	3	3			
Power at α = 0.05	0.415	0.582	0.463			
Type II error rate	58%	42%	46%			
A priori power analysis (minimum replicates required to achieve power of at least 0.80)						
Minimum replicates	6	5	5			

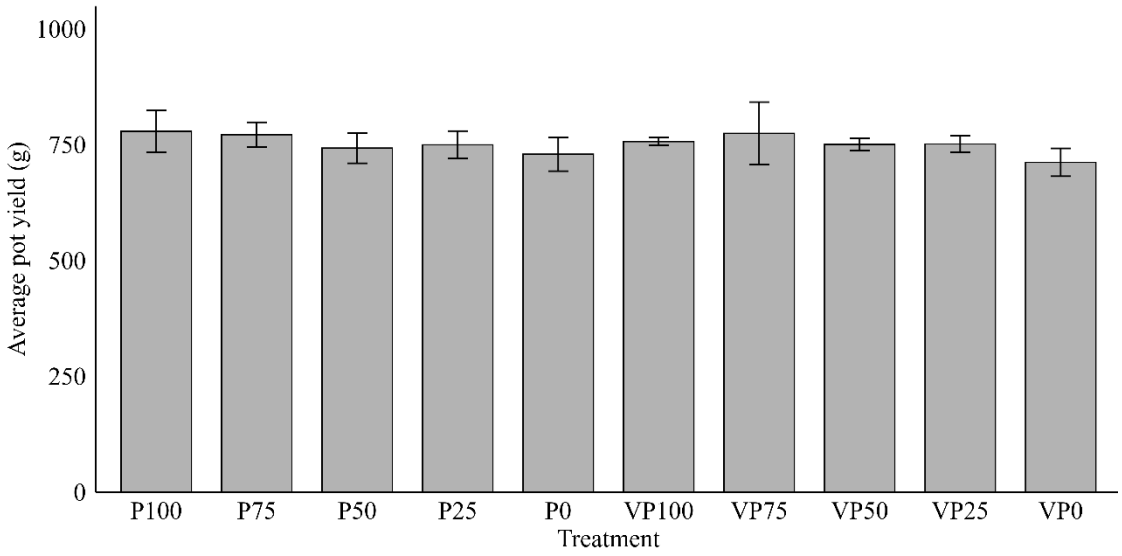


Figure 4-20: Average treatment yield per pot at harvest. Error bars are standard deviation.

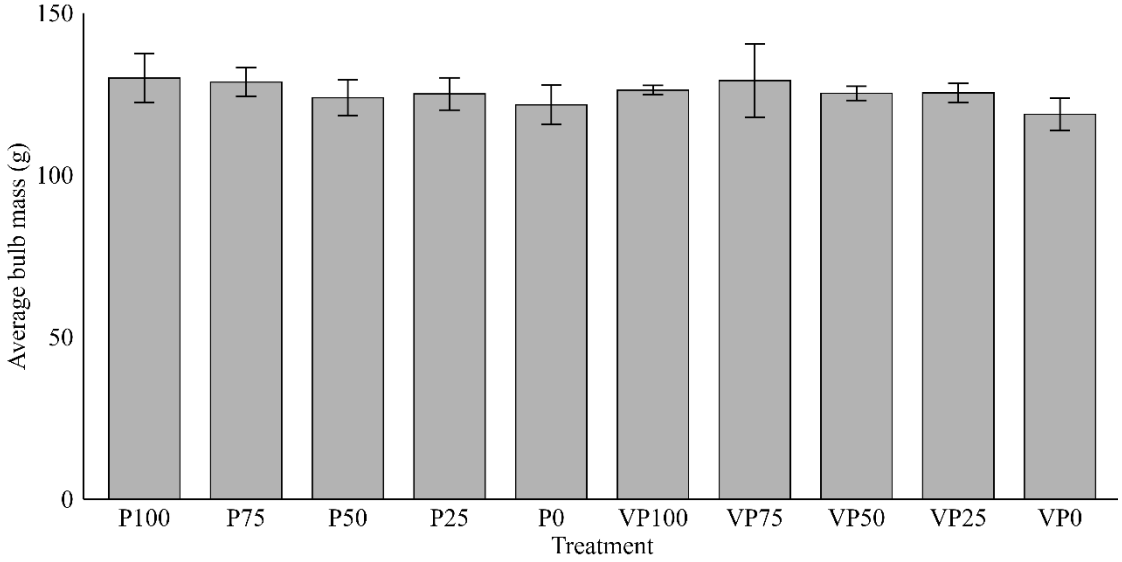


Figure 4-21: Average individual onion fresh mass per treatment at harvest. Error bars are standard deviation.

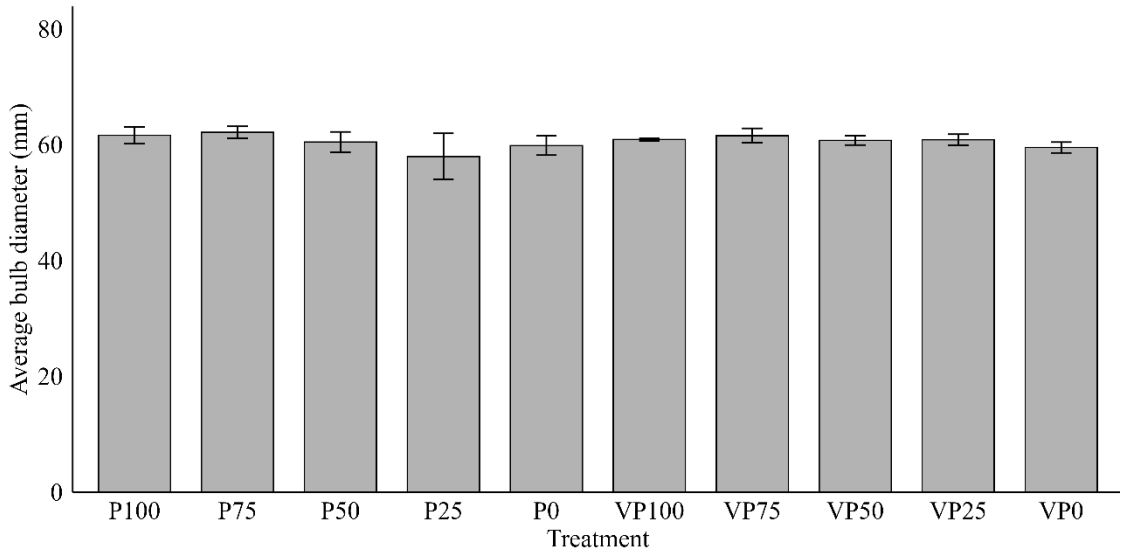


Figure 4-22: Average onion bulb diameter per treatment at harvest. Error bars are standard deviation. N.B. the 0.0 mm standard deviation for 0I is correct. All three replicate means were 62.7 mm.

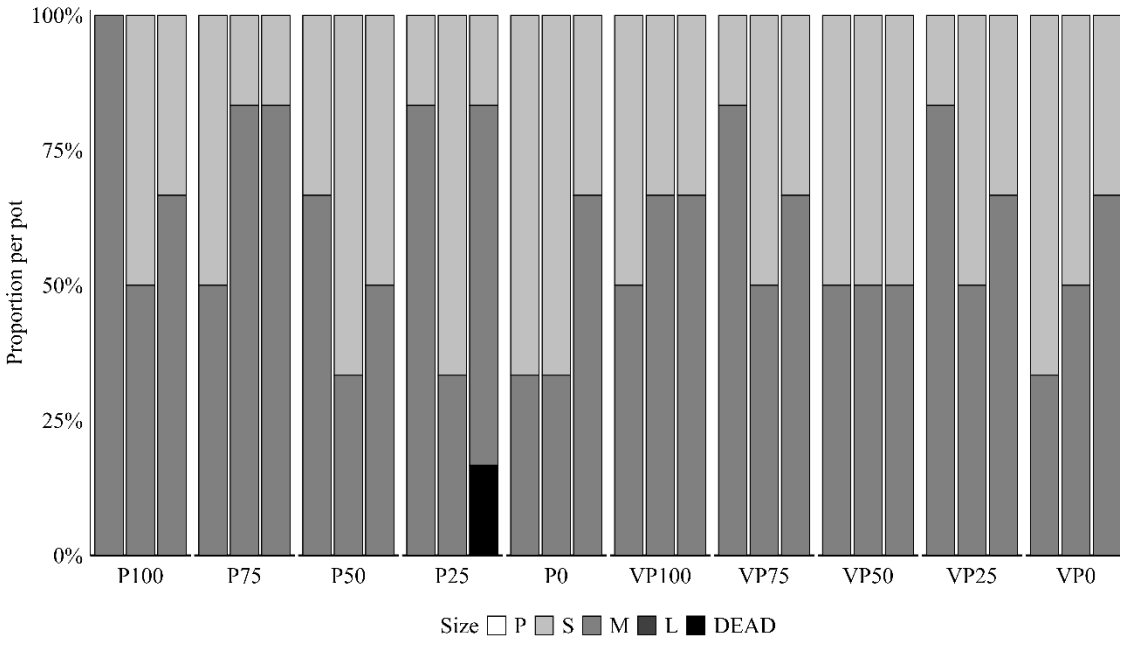


Figure 4-23: Proportion of onions in each size class (P = pickling, S = small, M = medium and L = large), including onions that died during the trial. Replicates (pots) are shown individually for each treatment (n = 6 onions per pot).

Most onions were in the medium size class, with the remainder in the small size class. There were no significant differences between treatments for number of small ($p = 0.503$) or medium onions ($p = 0.512$). There were no pickling or large onions in this trial. Only one onion died in one of the P25 replicates.

4.3.3.4 Trial 3 root dry matter production

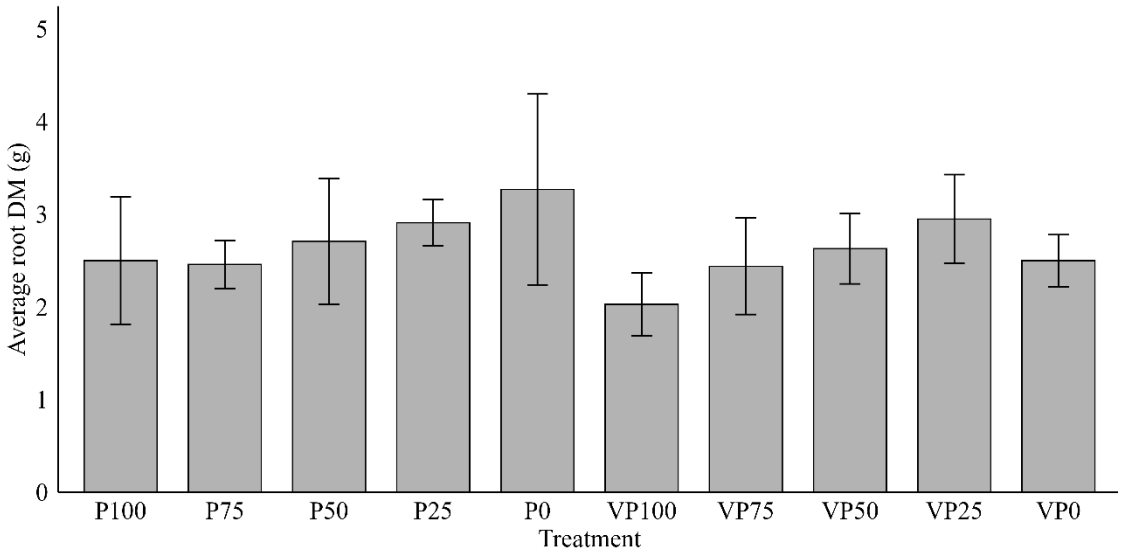


Figure 4-24: Average root dry matter (DM) per treatment. Treatments are the average of three replicates (pots, not onion plants). Error bars are standard deviation.

The Kruskal-Wallis test showed there were no significant differences in root DM with $p = 0.310$ (Table 4-23, Figure 4-24). A post-hoc power test showed that at $\alpha = 0.05$ and Cohen's $d = 0.092$, the power of this test (at $n = 20$ for Trial 1 and $n = 15$ for Trial 2) was 0.058. This is very low, indicating there was a 94% chance of missing a real effect if one existed, however with means of 2.34 and 2.30 and a Cohen's d of 0.092, the effect size is well below Cohen's threshold of 0.20 for a small effect.

4.3.3.5 Comparison of onion size distribution, Trials 1, 2 and 3

A comparison of onion size distribution between all three trials was carried out as there was a clear difference between Trial 1 conducted in the first season and Trials 2 and 3 conducted in the second season. Smaller onions were produced in Trial 1. This was confirmed by Kruskal-Wallis and Dunn's post-hoc tests with Bonferroni adjustment. There was no difference between Trials 2 and 3 for count of small or medium onions (Table 4-24). Vermicast application and P supply do not appear to have had an effect on onion size, rather this was due to different environmental conditions such as temperature and soil.

Table 4-24: Comparison of onion size distribution of small and medium onions in Trials 1, 2 and 3. Significant differences are indicated by "*" and significance letters a and b.

	n	Average count small onions	Average count medium onions
Trial 1	32	5.3 ± 0.9 a	0.16 ± 0.51 a
Trial 2	15	1.7 ± 1.0 b	4.33 ± 1.0 b
Trial 3	30	2.4 ± 1.1 b	3.57 ± 1.1 b
Kruskal-Wallis p value		*3.74x10-12**	*8.13x10-14**
Dunn's pairwise comparisons p values			
Trial 1 : Trial 2		0.000*	0.000*
Trial 1 : Trial 3		0.000*	0.000*
Trial 2 : Trial 3		0.314	0.291

4.4 Discussion

For comparisons between trials, refer to Appendix 2: glasshouse trial comparisons for onions. All graphs presented for Trials 1-3 are repeated in a table that allows easy comparison.

4.4.1 Trial 1: 2023-2024 timing of vermicast application trial

4.4.1.1 Trial 1 external influences

This trial was run concurrently with the field trials in Matamata. These are described in Chapter 5 (for results of the relevant onion trial, see Section 5.5.6.1). The same soil was used and the same fertiliser regime followed. However, the environmental conditions were quite different. It was observed that consistently high temperatures in the glasshouse may have limited overall onion growth. During the glasshouse trial, the cooling system malfunctioned and could not be repaired. The highest temperature recorded was 34.5°C which is above the optimal growing temperatures for onion crops – g enerally 20-27 °C during bulb development (Khokhar, 2017). As the ambient temperature exceeded 27 °C most days of the trial from mid-October onwards, temperatures exceeded the optimal range throughout bulb formation and development. Temperature is an extremely important abiotic factor in determining onion bulb size and therefore yield (Khokhar, 2017). The regular high temperatures experienced by all treatments under the glasshouse conditions are likely to have negatively impacted overall yields – this could be part of the reason why no large onions were produced in any treatments and the majority of onions fit the small size class, rather than the medium.

Another factor that affected the trial, but did not appear to impact treatments, was a leak in the glasshouse roof. This caused some pots to receive extra water early in the trial. In a few cases where vermicast had not yet been applied but the pots were

significantly wetter than the others, they were swapped with redundant extra pots that had been treated the same as the Control and vermicast treatments that had not yet been applied. At this point, except for 0B and 0I treatments which had already received vermicast, all other pots had been treated the same. Pots 0I2 and 2B4 received extra water through the roof leak but were kept in the trial as the amount was considered minor. These pots did not behave significantly different to any other pots therefore the trial outcomes were not affected by the roof leak.

4.4.1.2 Trial 1 effects of vermicast

The greatest number of seedlings emerged in the 0B treatment and these emerged faster than the Control. On average, it also produced the heaviest individual onions and the greatest average yield at harvest. However, none of these results were significant. Post hoc power analysis indicated that 21 and 11 replicates per treatment would have been required to achieve 80% power for seedling emergence and seedlings emerged respectively. This reflects high within-treatment variability relative to the small absolute differences between treatment means.

A study by Ievinsh (2011) reported the influence of different vermicompost extract concentrations on seedling emergence, including for onions. They reported that some species (carrot, tomato and parsley) were negatively impacted by vermicompost extracts at high concentrations, while cabbage, onion and Swedish turnips were less impacted by concentration. For the two *Allium cepa* onion cultivars used, germination rates were reported as 90 ± 6% (Stuttgarten Riesen – yellow cultivar, n = 6) and 40 ± 10% (Karmen – red cultivar, n = 6). The variation in the germination between cultivars is surprising and indicates there may have been an issue with the red onion seed line which may have affected the results. Overall, there did not appear to be an effect of vermicompost extract on onion germination, although higher concentrations (>50%) had a negative impact on the lengths of radicles and hypocotyls.

A study by Muhie *et al.* (2020) showed a beneficial on onion seed germination. A 5% concentration of 'vermicompost leach' used as a seed priming treatment significantly increased activity of the antioxidant enzymes catalase, ascorbate peroxidase and superoxide dismutase above the control and water-only priming treatment. They conducted another experiment in duplicate, comparing no treatment to water-only (hydro)priming and the 5% vermicompost leach (vermi)primer. In this experiment, the onion seeds were exposed to simulated extremes: drought (10 and 15% polyethylene glycol solution), salinity (50 and 100 mM NaCl) and temperature (30 and 35°C). The

vermiprimer treatment performed significantly better than the untreated seeds under all conditions in both experiments. In the second experiment, it performed better than the hydropriming in the 10% polyelthylene glycol solution, 35°C temperature, and both NaCl treatments, but not the 15% polyethylene glycol or 30°C treatments. Seedling emergence was also tested under similar conditions with the vermipriming treatment always performing significantly better than the control and outperforming the hydropriming treatment in four of the six treatments. These expreiments show that vermiproducts can stimulate enzyme activity in the seed and imrpove germination rates under varying abiotic stresses.

While acknowledging that the results were not statistically significant, it appeared that the broadcast (surface applied) vermicast that was in closer proximity to the germinating seeds, as opposed to the same quantity incorporated into the soil, resulted in faster emergence and more reliable germination. While the application methods were quite different to the previous studies discussed above, it is reasonable to assume that if vermicast were to have an effect on germination and emergence, applying the vermicast close to the seed would be more beneficial. This was also noted in the vermicomposting trial in Chapter 3, where vermicompost was applied to radish seeds either through broadcasting or incorporating into sand media or in its pure form as the growing media. The most beneficial treatment was the pure vermicompost, followed by the broadcast vermicompost. The least beneficial treatment was the incorporated treatment, though this still outperformed the Control. No statistical analyses were performed on these data as there were too few replicates (n = 2). Refer to Section 3.3.3.3, Figure 3-24.

On average across treatments, onion bulb mass was 71.9 g FM and most onions were classed as small onions (40-60 mm). The 0B treatment (12.5 t FM/ha vermicast broadcast at sowing) was the most similar treatment to the 12.5 t FM/ha vermicast treatment in the field trials conducted in Matamata (Chapter 5). As the trials were conducted concurrently on the same soil, they are compared here, demonstrating the effect of environment on plant growth (and noting the glasshouse onions were sown 18 days later than those in the field trials). Note that no significant differences were detected in either trial. However, according to Blouin *et al.* (2019), field trials are more likely to show beneficial effects of vermicompost application. The suggest this may be partly due to broadcast application (for field trials) rather than incorporation (for glasshouse trials) and/or promoting plants to respond to pests and diseases. The Control in the glasshouse trial produced an average bulb mass of 71.7 ± 2.7 g. Eighty eight percent of the glasshouse Control onions were classed as small onions. The Control in the field

trials produced an average bulb mass of 174.5 ± 8.9 g and 63% of onions were classed as medium (60-80 mm). The glasshouse 0B treatment produced an average bulb mass of 75.0 ± 4.4 g and 97% of onions were classes as small. The 12.5 t FM/ha (field trial equivalent) treatment produced an average bulb mass of 175.6 ± 13.4 g and 59% of onions were classed as medium. While no treatment effects were observed, these data clearly show the effect of environmental conditions with the field trials producing larger and heavier onion bulbs than those in the glasshouse trial.

In the glasshouse trial, the four pots with mortality showed higher average individual onion masses than the 28 pots without mortality (Wilcoxon rank-sum test, $p = 0.0007$), consistent with a density effect whereby surviving onions had access to more resources. This is consistent with a study by Jilani (2010) who reported that wider spacings resulted in greater onion mass and larger plants in three onion cultivars and concluded that less competition meant plants had more access to more resources such as light, nutrients and water.

The 1B treatment had the lowest root DM production, though this was not significant. It is possible that the lower root DM was related to the greater number of pickling onions (the smallest size class) than the other treatments – this was significant between this treatment and both 0B and 3B, however, there are no (significant or not) visible trends in relationships between other treatments and their root DM production.

4.4.2 Trial 2: 2024-2025 timing of vermicast application trial

4.4.2.1 Trial 2 (and Trial 3) external influences

The temperature conditions for Trials 2 and 3 were better for onion bulb production as average daily temperatures did not exceed 24°C. Except for a few days in early January where average temperatures dropped to ~19.2°C, they remained within the 20-27°C optimal for bulb production, as reported by Khokhar (2017). There were no issues with roof leaks.

During the trial, it was noted that the onions leaves tended to ‘sprawl’, rather than maintain an upright habit. The cause of this was not investigated as the onions were still developing and appeared healthy. Their development also appeared to occur at a faster rate than for Trial 1, which was assumed to be limited by temperature conditions.

As resources were limited for Trials 2 and 3, fewer replicates were possible for each treatment. This led to the sharing of Controls and 0B (vermicast broadcast at sowing) pots between the trials. This was assumed to have no effect on the trials as all were treated

the same. However, as soil cores were removed monthly during the growing period from the Trial 3 pots, they had to be taken from all Trial 2 pots as well.

The non-normal distribution of the data was likely due to low replication in this trial (three replicates per treatment).

4.4.2.2 Trial 2 effects of vermicast

There were no significant results in this trial. As the broadcast vermicast treatment in Trials 1 and 2 show that seedlings germinated faster with vermicast (Figure 4-6 and Figure 4-13), it is again worth considering that there may have been a beneficial effect of the vermicast used in seedling survival and emergence (refer to Section 4.4.1.2 for Trial 1 discussion), but the power of the statistical tests was too low to detect a difference at n = 4 and n = 3. Post hoc power analysis indicated that 42 and 10 replicates per treatment would have been required to achieve 80% power for seedling emergence and seedlings emerged respectively. This reflects the small observed differences between treatments for emergence, but reflects high within-treatment variability relative to the small absolute differences between treatment means for seedlings emerged.

Overall, the onions in Trial 2 performed better than the onions in Trial 1 – they were heavier, larger in size and grew almost twice the yield. Note that seed from the same batch was used for both trials. Interestingly, the root mass was the same between the two trials, indicating that root growth may not increase with larger bulbs under conditions where physical constraints (pot volume) are in place.

4.4.3 Trial 3: 2024-2025 phosphorus supplementation trial

Trial 3 shared the same soil and analysis methods as Trial 2. See Section 4.4.2.1 for discussion on external influences for Trial 2.

4.4.3.1 Trial 3 effects on onions

Although Trial 3 produced greater yield and larger onions than Trial 1 (the previous season), there was no effect of P treatment on onion size, mass or root DM production. A trial by Hayman and Mosse (1971) showed that the size of onion growth response was not correlated with the amount of PO_4^- in the soil. Instead, the presence of mycorrhizal fungi had more influence on onion growth.

Onion sizes were larger in Trials 2 and 3 compared to Trial 1. The main differences were season, glasshouse temperature (cooler for Trials 2 and 3) and soil.

Onion growth in the trial may have been restricted by the environmental conditions. For example, the root masses between Trials 1 and 2 were the same although

the yield from Trial 2 was about twice as great as the yield from Trial 1. This indicates that perhaps the pot volume limited root growth. Note that Trial 3 and Trial 1 were not directly compared to each other as the trials tested different things (timing vs P supplementation). Root restriction could be overcome by conducting a field trial. However, the advantage of the soil homogeneity achieved in Trial 3 would be lost.

Observations were made on the frequency of leachate draining from the pots after watering. This was assumed to be partly due to the large holes made by the soil corer when collecting samples for Olsen P testing – the water could easily drain through. However, an informal observation was made that the treatments without vermicast were almost twice as likely to leach water than those that had not received vermicast. All pots were watered the same throughout the trial as per Section 4.2.2.3 i.e. they received the same amount of water. The difference in leaching frequency could be due to a few factors. First, leaching frequency was not recorded at every opportunity (three-daily watering). Differences may therefore reflect when an observation was made, rather than a genuine difference between vermicast and non-vermicast treatments. Second, the vermicast may have increased the fraction of small roots (finer than those extracted by sieving) increasing access to water and therefore water use. This is supported by the results of a meta-analysis by Blouin *et al.* (2019) who showed that vermicompost applications increased root biomass by 57% across a variety of species, but not specifically including *Allium* species. However, there was no difference in root DM production between treatments in this trial. Third, water requirements likely varied as onions grew. While weekly measurements of onion bulb diameter were made, the data were not analysed as there was too much noise. The bulbs were not perfectly symmetrical and as they grew, it became more difficult to measure them across the same points without causing damage to nearby plants. While these data are not reported in this thesis, it was informally observed that smaller onions were more likely to leach and the soil surfaces of pots with smaller onions were more likely to appear damp at the next watering. If this trial were to be repeated, rate of change in bulb size would be interesting to record, though it would be prudent to ensure that crowding would not affect data collection.

4.4.3.2 Trial 3 final soil Olsen P

The higher Al in the trial soil could be related to the soil's volcanic origins. This soil is a representative of the Mangakahu family (Mangakahu_20a.1 sibling (Manaaki Whenua, 2024), and is classified as a Typic Orthic Allophanic soil (Hewitt, 2010). It was shown to contain a moderate level of allophane, an aluminosilicate clay mineral known

to limit P availability through sorbtion of PO_4^- (Bolan, 1991). It is reported to have high (83%) topsoil P retention (P retention is equivalent to ASC). While this is lower than the >98% ASC reported for the trial soil (Table 4-17), it is still considered high (Manaaki Whenua, 2024). These factors reduce soil P availability. In addition to this, the vermicast was noted to have a high Ca content (692.72 mg/kg DM). The inputs for the vermicast included pulp and paper mill primary solids. Calcium carbonate is used in paper production (Hu *et al.*, 2022) and therefore likely makes up a large proportion of the calcium forms in the vermicast. Calcium carbonate is recognised to reduce PO_4^- solubility and availability (Cole *et al.*, 1953) so P solubility of the vermicast may be reduced. Although testing of water extractable P (WEP; results not reported) indicated that P was more readily extracted from the vermicast than the soil at ratios of 1:5 to 1:300 of soil/vermicast to water (the vermicast had >300x more WEP than soil), water soluble P testing in the vermicomposting trials against NZS 4454:2005 (Chapter 3), indicated that P availability was low (it was less than the batch blank). Note that water extractions are not analogous to Olsen P where the pH of the NaOH extraction solution is 8.5, which directly affects the chemical availability of P (Olsen *et al.*, 1954). Olsen P content of the vermicast was not measured as it is not a test designed or calibrated for this kind of material. In addition to the high Ca content, the vermicast was produced outdoors over a period of 12 months or so, which exposes it to weather conditions conducive to leaching and therefore loss of nutrients such as water-soluble P prior to the trial. The combination of factors affecting P availability make it difficult to determine whether the vermicast itself supplied significant quantities of P, though this does not appear to be the case as there were no differences in final Olsen P content between vermicast and non-vermicast treatments.

The final Olsen P contents of the soils are not absolute as the blanks had greater Olsen P concentrations than the soil samples. Thirty-two soil samples (from the trials in Chapter 5) were also prepared and tested in the same batch and did not have this issue. The low Olsen P results in the Trial 3 soils was attributed to the known low Olsen P level of the soil, likely or partially due to the presence of allophane and very high ASC properties of the trial soil. The other caveat is that the onions would have taken up P as they grew, affecting soil P content. The Olsen P results reported here are for comparative purposes only (see Section 4.2.3.2 in the methods and Table 4-17 in the results for further comments). These results cannot be compared to the initial Olsen P. However, a statistically significant difference in soil final Olsen P was detected between the Control (P100), the two vermicast treatments with the highest DAP application rates (100% and

75%) and the treatment that received no DAP fertiliser. This test had high power (99.2%), indicating the risk of a Type II error (false negative) is very low so it is unlikely that the vermicast had an undetected effect on any other treatments.

The application of vermicast to the soil did add P equally across all vermicast treatments (about as much as the DAP-P applied to the P25 and VP25 treatments: 0.08 g P/pot). This did not appear to affect the Olsen P contents of the soils as there was no obvious difference between vermicast and non-vermicast treatments. Table 4-11 reports the actual P applied as DAP per treatment – ranging from 0.1 g P/pot for the P25 and V25 treatments to 0.38 g P/pot for the P100 and VP100 treatments. The application of vermicast appears to have had an effect on P availability, but only at higher P application rates i.e. 75 and 100% of recommended DAP application rates as these were not different to the Control.

Anion storage capacity (ASC) is a soil's ability to bind negatively charged nutrients like PO_4^- and SO_4^-. A high ASC, as reported in this soil (>98%) indicates P availability will be limited. As stated, the soil's initial Olsen P was low at 14.7 ug P/kg soil. This in conjunction with the high ASC predisposed the soil to be a poor supplier of P, though total P (TP) was reported to be 'medium' at 1,254 mg/kg soil. According to Hill Laboratories (n.d.-a), Olsen P for high ASC soils tends to be 1.4% of Total P. In this soil, it was calculated to be 1.2%.

According to Saunders (1965), soil P retention (also referred to as ASC) depends on the parent material and degree of weathering. Soil P retention was reported to peak in moderately weathered silty soils and decline in weakly and strongly weathered soils. They also reported volatile solids content (loss on ignition = organic matter + inorganic colloids) was significantly correlated with P retention in A horizons/topsoils i.e. higher volatile solids, meant higher P retention). Tamm Al is a measure of reactive (oxalate-extractable) Al. Higher Tamm Al also resulted in higher P retention with the exception of allophanic soils (high Tamm Si) which have lower P retention per unit Tamm Al than crystalline soils. For some soil groups, Tamm Fe and Tamm Al together give a better indication of P retention. This kind of information was unavailable for the studied soil, however it shows that P retention is dependent of multiple factors e.g. geological age/degree of weathering, parent material, organic matter content and the reactivity of certain elemental compounds. Being classed as an allophanic soil (which are known to have an affinity for P retention), it is unsurprising that the initial test report indicated a very high ASC for the trial soil (>98%).

4.4.4 Statistical power

The results of all three trials indicated that too few replicates were used to achieve statistical power of $1 - \beta = 0.80$. Despite generally large observed effect sizes (Cohen's $f > 0.40$), high within-treatment variability relative to the small absolute differences between treatment means often resulted in a large number of recommended replicates to achieve adequate power. The issue with low power is the high probability of statistical tests such as ANOVA and Kruskal-Wallis returning non-significant results even when a true treatment effect actually exists. This is known as Type II error or false negative. The non-significant results in these trials should be interpreted with caution, as they may reflect insufficient statistical power rather than a genuine absence of treatment effects. This is especially relevant for the seedling emergence trials as the same treatment trend was observed in both Trials 1 and 2. Even though it was not significant under the trial conditions, it was noted that the Control treatment was outperformed by the Incorporated and Broadcast treatments in both trials (and the Broadcast treatment outperformed both the Control and Incorporated treatments). The differences were small, but as the same trend was observed in two different soils and growing seasons. This indicates vermicast may have a beneficial effect on onion seedling emergence at a rate of 12.5 t FM/ha.

To increase statistical robustness in future trial designs, greater numbers of treatment replicates are recommended. Appropriate replicates based off a priori analysis have been reported in tables for each trial in Section 4.4.

4.5 Conclusions of all three glasshouse trials

Trial 1 produced smaller onions than Trials 2 and 3. This was attributed to environmental conditions (temperature and soil). Hotter temperatures were experienced in Trial 1 which used an intensively cropped soil as the growing media. Trials 2 and 3 were grown under cooler, more favourable temperatures and used soil from land under pasture in Ohakune.

Vermicast application method (incorporated into the soil vs the same rate broadcast on top) had no statistically significant effect on seedling emergence or number of seedlings emerged. However, the same trend observed in Trials 1 and 2 indicate there may be an effect that is not able to be detected with small sample sizes. Low statistical power due to insufficient replicates was identified for measurements performed on onions across all three trials.

The vermicast trialled did not appear to have a beneficial effect on onion production under glasshouse conditions. The timing of the application of vermicast did

not affect yield, bulb mass, size or mortality. Environmental factors such as season, temperature and/or soil had an effect on bulb mass, size and yield, but not root DM production. Under the trial conditions, root DM production was the same between the two seasons, despite the increases in bulb size and almost doubling of yield and bulb mass.

Trial 3 showed that final soil Olsen P content was significantly lower in P0 (no vermicast, no DAP fertiliser) than the three treatments P100 (Control), VP100 (vermicast + 100% DAP) and VP75 (vermicast + 75% DAP).

Vermicast applied at 12.5 t FM/ha supplied P to the soil and appeared to supplement reductions DAP fertiliser applications. Final soil Olsen P under VP75 was not significantly different to the Control (P100), suggesting that vermicast may supplement DAP fertiliser by up to 25% on low Olsen P soil without reducing soil P availability. The effect on onion mass, size and root DM production could not be determined, as these measurements were underpowered.

Chapter 5

Plant production: field vermicast experiment

Vermicast[6] derived from milk processing dissolved air flotation (DAF) sludge and pulp and paper mill solids (fibre) was applied to maize, potato and onion crops over three consecutive years on a commercial market garden. The effectiveness of vermicast at increasing crop yield and quality was compared to chicken litter application and control treatments.

Chapter 5 first reports the trial design and methodologies for the plant production trials, starting with a description of the experiment site, then the experimental design, sampling methods, statistical methods. The results and discussion sections report on each of the trialled crops individually. The order of this is onions, potatoes then maize. Within each crop, results for each of the three seasons are reported individually in sequential order and then compared in a multi-season analysis.

In this section, "experiment" refers to the entire three-year field experiment, which consisted of three "Trials" (Trial A, B and C). "Plot" refers to one replicate of a single treatment.

5.1 Site description

The experiment was carried out over three consecutive growing seasons from September 2022 to June 2025. The experiment site was north of Matamata township, in the Waikato region, North Island, New Zealand (37.7922° S, 175.7732° E). This was on a commercial market garden farm owned and operated by Balle Bros Growers Ltd. Local weather data was supplied by MetWatch (https://www.hortplus.com/) from a station located south east of Matamata township, <10 km from the trial site. Based on 1991–2020 climate data obtained from NIWA DataHub (https://data.niwa.co.nz/), the experimental site receives an average annual rainfall of 1291 mm (Okauia station 6.5 km east of then experiment site) and experiences a mean annual temperature of 13.4 °C (Hinuera station 10 km southwest of then experiment site).

The soil at Trial C, with a silt loam topsoil, is a representative of the Otorohanga family (Otoro_74a.1 sibling (Manaaki Whenua, 2025c), and is classified as a Typic

[6] The White Gold vermicast tested in Chapter 3 was deemed to be a vermicompost, not a vermicast under the voluntary NZS 4454:2005 composting standards. However, as the White Gold product was received and used in this trial as a vermicast, it will be referred to as a vermicast in Chapters 4 and 5.

Orthic Allophanic soil. The soil at Trial B, with a silt-dominated topsoil, is a representative of the Bruntwood family (Brunt5a.1 sibling (Manaaki Whenua, 2025a)), and is classified as a Mottled Orthic Allophanic soil (Hewitt, 2010). The soil at Trial A, with a silt-dominated topsoil, is a representative of the Matuku family (Matu_14.2 sibling (Manaaki Whenua, 2025b)), and is classified as an Acidic Orthic Gley soil (Hewitt, 2010). Detailed descriptions of the site's soils are included in Section 5.5.1.

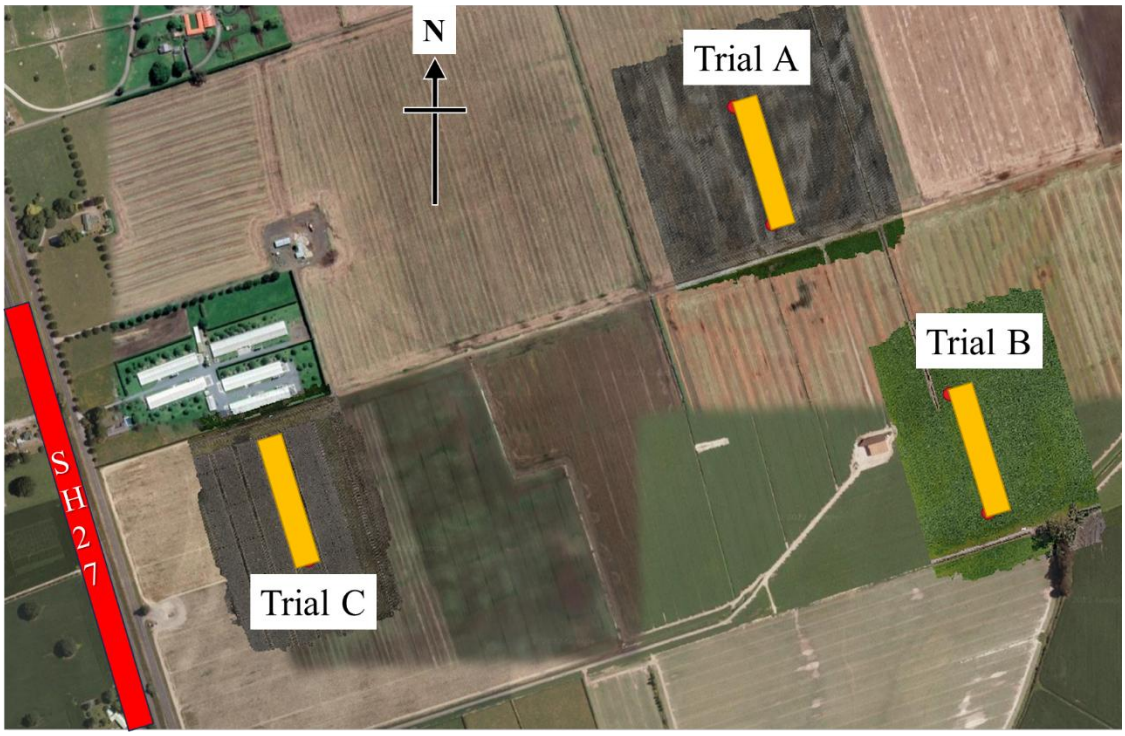


Figure 5-1: Satellite image of Matamata market garden site. The trial locations are labelled and highlighted in yellow. State Highway 27 (SH27) is marked as a red rectangle.

In any one growing season, three main crops (maize, potatoes and onions) are grown in separate areas on this farm. These crops are rotated seasonally to avoid disease build up and 'rest' the soil from the nutrient demands of each crop. Occasionally, a clover or Italian ryegrass cover crop is grown over winter and sold as baleage (bales for stock feed). This is dependent on harvest dates of previous crops, planned sowing dates of the following crops and environmental conditions at the time. During this three-year experiment, the soil was usually fallowed over winter. Three trial sites (A, B and C) were selected for this experiment (Figure 5-1). The aim for site selection was to select three sites that represented the larger area that each of the three major crops were grown on. The trial sites were to be as homogenous as possible i.e. already providing the most consistent yields prior to the trial starting. The sites were selected based on (i) grower knowledge of the history and performance the market garden farm, (ii) satellite imagery indicating differences in land use since 2003, (iii) visual observation of the homogeneity of crop growth and slope on farm prior to beginning the experiment, including recent

drone imagery. Specific areas were avoided during site selection. These were areas that had received vermicast in a pilot trial in 2021, crop headlands and existing and infilled drains as these areas are known to have variable nutrient and water availabilities.

5.1.1 Soil profile

Soil profiling was carried out on each of the three trial sites in September 2022 using a 2" Dutch auger to an average depth of 1 m. Profiles were described following the New Zealand Geotechnical Society Guidelines for field descriptions (New Zealand Geotechnical Society Inc., 2005). Descriptions included texture, colour, plasticity, moisture, mottling, depth of changes and allophane reactivity. Five profile descriptions were made per trial site: one in each corner and one in the middle of the trial area. The samples were triple bagged for transport back to the University of Waikato for moisture content analysis. The remaining sample material was air-dried and archived for further testing.

5.2 Experimental design

The experiment was designed to integrate into the market garden farm in three separate locations (Trials A, B and C), with minimal disturbance to commercial activity over three years. Plot and buffer sizes were set to minimise disruption to the trial plots via machinery and commercial activities.

The grower used GPS coordinates to lay crops and plan tram lines (paths used by spraying and fertilising machinery throughout the growing season). Irrigator tracks for the travelling lateral irrigator were reformed in the same place each year. Despite some variation, the consistency of the path formation made it possible to predict the best location for each of the three trials (A, B and C) to accommodate each of the three different crops (maize, potatoes and onions) with minimal loss of plot area to machinery paths. Figure 5-2 shows the trial layout, including location of the plots relative to the tram lines and irrigator tracks.

5.2.1 Soil drag

Soil drag was an important consideration in the design of this trial. Soil drag in this thesis refers to the transfer of soil into or out of a plot's defined area through cultivation, sowing and harvesting activities. The same concept also applies to the movement of vermicast or chicken litter outside a plot's defined area. Commercial cropping activities routinely employed on the farm are known to drag soil. These activities were also expected to drag vermicast/chicken litter to outside of/into other plot

areas. As the experiment was planned to be repeated in each GPS-logged trial location for three consecutive years, long plot areas, running in the same direction as commercial activities (north-south) were used. This was to increase the available sample size area which was expected to be reduced through drag. This would also minimise the potential for vermicast and chicken litter applications to be diluted and avoid edge effects during sampling. Buffer zones were incorporated into the design to avoid contaminating treatments with vermicast/chicken litter. The length of these buffer zones was set at 20 m, the same length as the plots, based on grower estimates of soil drag during expected cultivation activities (Table 5-1) and the 50 m spacings of the irrigator tracks. Over the three-year duration of the experiment in any one trial area, the total estimated distance of soil drag was between 24.5 and 33.5 m. Because cultivation occurs in both directions (soil, and vermicast/chicken litter applied to plots, would be dragged backwards and forwards, see Figure 5-2), and cover crops are not always sown, it was assumed that 20 m of buffer would be sufficient to avoid cross contamination of treatments.

Table 5-1: Estimated soil drag due to routine cultivation activities (personal communication, Tim Balle, September 5, 2022).

Crop	**Activity**	**Estimated soil drag (m)**	
		Low	**High**
Potatoes	Disc	1	1
	Rip	1	1
	Power harrow	3	5
	Plant	4	5
	Harvest	3	3
Sub total		12	15
Cover crop	Annual crop cultivation	1	2
Sub total		1	2
Onions	Rip	1	1
	Power harrow	3	5
	Roll and drill seed	0.5	0.5
	Lift and harvest	0.5	0.5
Sub total		5	7
Cover crop	Annual crop cultivation	1	2
Sub total		1	2
Maize	Disc	1	1
	Rip	1	1
	Power harrow	3	5
	Plant	0.5	0.5
	Harvest	0	0
Sub total		5.5	7.5
Total (over 3 years)		24.5	33.5

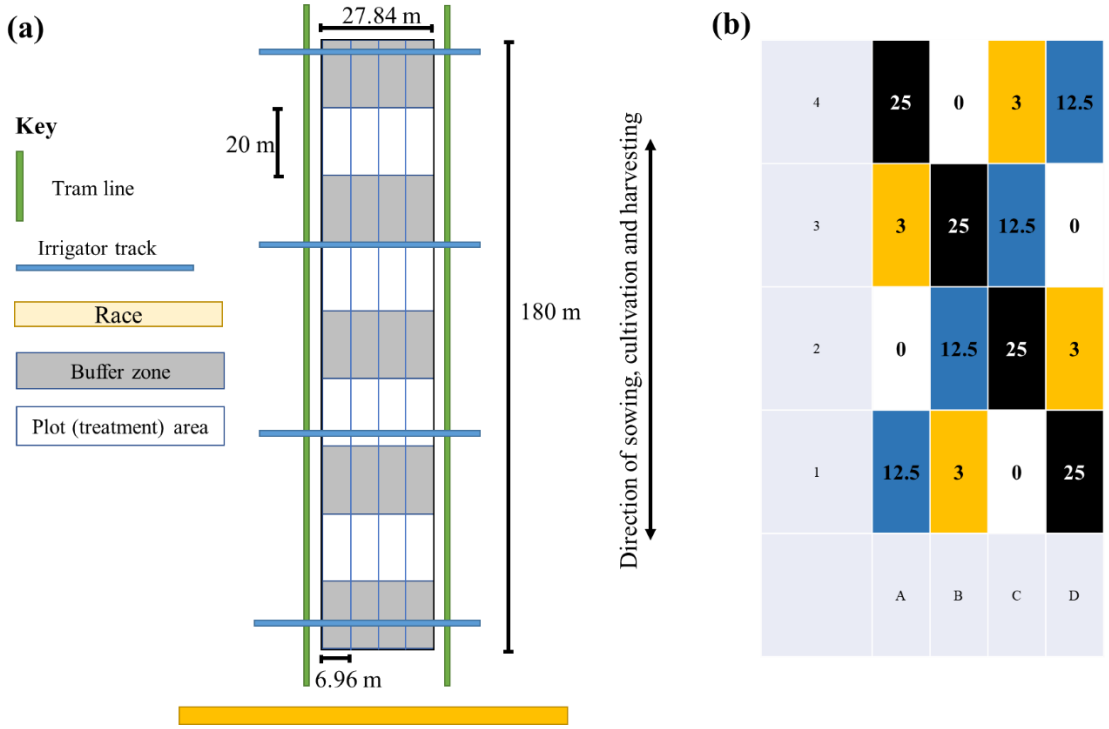


Figure 5-2: (a) Trial layout, showing dimensions, buffer zones and machinery tracks. Tram lines are the paths used for spraying and fertilising crops throughout the growing season. Irrigator tracks are the paths that the travelling irrigator used. Not to scale. (b) Latin square pattern used for treatments and replicates. White (0) squares represent the Control plots, orange (3) squares represent the 3 t fresh matter (FM)/ha chicken litter treatments, blue (12.5) squares represent the 12.5 t FM/ha vermicast treatments, black (25) squares represent 25 t FM/ha vermicast treatments.

5.2.2 Plot placement, size and spacing

Three treatments: chicken litter at 3 t fresh matter (FM)/ha/yr, vermicast at 12.5 t FM/ha/yr and vermicast at 25 t FM/ha/yr were trialled alongside a Control. All treatments were applied in addition to normal farm management. Trial areas were treated the same as the commercial crops, i.e. chemical/mineral fertiliser and pesticide/herbicide/fungicide applications were the same between treatment and Control plots. Each treatment was replicated four times. The sixteen resulting plots were arranged in a Latin square where each treatment occurred once in each row and column (Figure 5-2).

Treatments were randomised by assigning a number (1-4) to each treatment and the Control. Using the "=RANDBETWEEN(1,4)" function in Excel, each of the four treatments were assigned to plot in each row, ensuring that treatments were not duplicated in any row or column. This was an important feature of the trial design as results of a pilot trial from 2021-2022 on the same market garden farm showed an effect of the column samples were taken from in an onion crop. The same treatment layout was used in each of the three trials (Figure 5-2).

The sizes and spacings of the plots were deliberate. Each plot was 6.96 m wide x 20 m long (139.20 m^2). The width of the plots was calculated to accommodate the different widths of crop beds. An onion bed was 1.75 m wide, including one wheel track (actual bed area was about 1.4 m wide) and eight rows of onions. Maize rows sown were 0.76 m apart. Potato mounds were 0.87 m wide. A 1 m sampling buffer from either end was incorporated into each plot. Because each crop had different bed sizes, the tram lines formed to manage each crop through the growing season shifted with each crop. The approximate tram line locations (GPS paths used by commercial spray and fertiliser machinery) were predictable. The trial locations were planned so that the tram lines (spaced approximately 30 m apart) surrounded the trial (27.84 m) without interfering with the sampling area. Although GPS was used to form them, there was variation in the placement of the tram lines, but this did not affect the sampling areas. Note that in Trial A, Season 1 (onions), a tram line was placed within Column A instead of being outside the trial area. The layout was not adjusted because this would have caused tram lines to affect crops in Seasons 2 and 3 (refer Figure 5-2 (a)).

After general areas for the three trials had been selected, ArcMap 10.8.2 was used to generate GPS coordinates using the NZGD2000/Mount Eden 2000 projection for the plot and buffer corners. These were loaded onto a Leica Viva GS16 GNSS unit and used to place visual markers for the trials throughout the three-year experiment (markers could not stay in place while cultivation activities occurred). This unit was also used to set for ground control points for drone imagery.

5.3 Crop varieties and farm management

Over the three years, crop management involved cultivation activities, irrigation, herbicide, fungicide and insecticide spraying as well as mineral fertiliser applications. Cultivation activities are listed in Table 5-1, while irrigation, spray and fertiliser applications are listed below.

5.3.1 Onions

Onions (Rhinestone variety) were sown in winter (Table 5-6). Each season, pre-emergence herbicides were applied, followed by weekly post-emergence herbicide applications until November. Fungicides and insecticides to manage downy mildew (*Peronospora destructor*), white rot (*Sclerotium cepivorum*), *Botrytis*, *Stemphylium*, *Alternaria*, thrips (*Thrips tabaci*), onion maggot (*Delia antiqua*), cutworm (*Agrotis ipsilon*) and bacterial infections such as bacterial soft rot (*Erwinia spp.*) were applied for five months while the bulbs were developing between November to February.

Onions were only irrigated in Season 3 (December 2024).

5.3.2 Potatoes

Potatoes (Crop 78 variety in Seasons 1 and 2 and Moonlight in Season 3) were sown November-December (Table 5-6). Each season, pre-emergence herbicide was applied. A desiccant was applied in late autumn to kill-off the haulm (shoot) and manage weeds where crops were not harvested until spring. Fungicides were used to manage *Phytopthera, Alternaria*, *Sclerotinia* and *Fusarium* from November to April. Insecticides were applied from January to April to manage aphids, tomato potato psyllid and potato tuber moth.

Potatoes were irrigated in Season 2 (January and February 2024) and Season 3 (December 2024 – March 2025).

5.3.3 Maize

Maize was sown in October each season. In Seasons 1 and 2, the variety sown was destined for grain. In Season 3, the variety sown was destined for silage. For maize crops, herbicide was applied monthly from October to December. A fungicide and insecticide application was made in November.

Maize was irrigated in Season 3 (January 2025).

5.3.4 Clover

An annual Persian clover cover crop followed the onion crop in Trial A. The clover was sown on 13th April 2023 after cultivation. No base fertiliser was applied, although a 0.080 t/ha side dressing of SustaiN® was applied on 30th August 2023. The crop was harvested on 6th October 2023.

5.3.5 Fertilisers

Fertilisers, nutrient contents and applications for each crop are reported in Table 5-2 to Table 5-5.

Table 5-2: Fertiliser regime for onion crops over the three growing seasons.

	Base fertiliser			Side dressing		
	Date applied	**Fertiliser**	**Rate (t/ha)**	**Date applied**	**Fertiliser**	**Rate (t/ha)**
Season 1	3/08/2022	Ag Lime	5.200	7/09/2022	DAP	0.311
2022-2023	4/08/2022	Serpentine Super 7k	0.743	12/10/2022	Nitrophoska Extra	0.290
Trial A				23/11/2022	Nitrophoska Extra	0.338
				31/12/2022	Nitrophoska Perfect	0.350
Season 2	9/08/2023	Serpentine Super 7k	0.500	21/09/2023	DAP	0.300
2023-2024				25/10/2023	Compound Extra	0.300
Trial C				28/01/2023	Compound Premium	0.350
				20/12/2023	Compound Premium	0.350
				22/01/2024	YaraBela CAN	0.075
Season 3	6/06/2024	Ag Lime	3.000	5/09/2024	DAP	0.300
2024-2025	9/07/2024	Waikato Onion Base Mix	0.750	2/10/2024	Compound Premium	0.300
Trial B				2/11/2024	Nitrophoska Extra	0.250
				5/12/2024	Nitrophoska Extra	0.350

Table 5-3: Fertiliser regime for potato crops over the three growing seasons.

	Base fertiliser			Side dressing		
	Date applied	**Name**	**Rate (t/ha)**	**Date applied**	**Name**	**Rate (t/ha)**
Season 1	1/11/2022	2022 Waikato Base Mix	0.800	3/01/2023	YaraBela CAN	0.300
2022-2023	4/11/2022	2022 Waikato Potato Planting Mix	1.400	17/01/2023	Nitrophoska Extra	0.515
Trial B						
Season 2	4/12/2023	2023 Waikato Base Mix	0.450	9/01/2024	Compound Premium	0.650
2023-2024	5/12/2023	2023 Waikato Potato Planting Mix	1.400	2/03/2024	YaraBela CAN	0.400
Trial A						
Season 3	13/11/2024	2024 Waikato Base Mix	0.450	27/12/2024	YaraBela CAN	0.300
2024-2025	13/11/2024	2024 Waikato Planting Mix	1.400			
Trial C						

Table 5-4: Fertiliser regime for maize crops over the three growing seasons.

Maize	Base fertiliser			Side dressing		
	Date applied	Name	Rate (t/ha)	Date applied	Name	Rate (t/ha)
Season 1	11/10/2022	Serpentine Super 7K	0.450	25/11/2022	SustaiN	0.400
2022-2023	12/10/2022	YaraMila Actyva S	0.350			
Trial C						
Season 2	9/10/2023	Serpentine Super 15K	0.600	2/12/2023	SustaiN	0.350
2023-2024	12/10/2023	YaraMila Actyva S	0.350			
Trial B						
Season 3	1/10/2024	Serpentine Super 15K	0.500	29/11/2024	SustainN	0.350
2024-2025	29/10/2024	YaraMila 12-10-10	0.400			
Trial A						

Table 5-5: Nutrient content of fertilisers used on Trials A, B and C in Matamata. Nutrient content is reported as percent weight of element by product weight. N = nitrogen, P = phosphorus, K = potassium, S = sulphur, Mg = magnesium, Ca = calcium.

	N	P	K	S	Mg	Ca
Ag Lime						40
Compound Extra*	*12*	*5.2*	*14*	*8*	*1.2*	*3.8*
Compound Premium*	*12*	*5.2*	*14*	*8*	*1.2*	*3.8*
DAP	18	20		1		
Nitrophoska Extra	12	5.2	14	8	1.2	3.8
Nitrophoska Perfect	15	2.2	16.6	8	1.2	2
Serpentine Super 15K		4.76	15	5.95	3.5	1.55
Serpentine Super 7k		5.78	7.5	7.23	4.25	14.03
SustaiN®	46					
YaraBela CAN	27					
YaraMila 12-10-10	12	10	10			
YaraMila Actyva S	15	7	12.5	3	1.2	
Waikato Potato Base Mix			31.5	18.5	37.5	
Waikato Potato Planting Mix†	8.6	6.8	10	10	2.66	5.1
2024 Waikato Onion Base Mix‡		6.8	7.5	1.27	4.5	15

*Compound Extra and Compound Premium have been discontinued, but were similar products to Nitrophoska Extra. The nutrient content of the Compound products in italics have been copied from Nitrophoska Extra.
†Also contains 2.3% boron.
‡Also contains 0.6% zinc

5.4 Methods

5.4.1 Collection and storage of vermicast and chicken litter

5.4.1.1 Vermicast

In 2022, approximately 20 t of vermicast (enough for the three-year trial with excess) was sourced from a commercial supplier in Putaruru, South Waikato, New Zealand in 2022. The quantity of vermicast required for the trial was estimated by volume, using a bulk density of 0.7 t/m^3. The feedstock for this vermicast was DAF sludge and Waste Activated Sludge (WAS) from milk processing combined with waste fibre from pulp and paper processing. The feedstock was mixed in a Strautmann Verti-Mix 2401 double auger mixer wagon before being laid as a vermicomposting windrow in a paddock until vermicast maturity (approximately 12 months) before harvesting and screening to 2 mm.

The vermicast required for Seasons 2 and 3 was stored, outdoors in Tokoroa (56 km south of the trial site) under an impermeable plastic cover, in woven plastic 1 t bags on wooden pallets. After the application of vermicast in Season 1, it was calculated that there would not be enough vermicast to finish the three-year trial. The bags stored at the Tokoroa site were emptied and additional vermicast derived from milk processing DAF sludge/WAS and waste fibre from pulp and paper processing was mixed

into it. The mixed vermicast was rebagged in the 1 t bags and stored in a storehouse in Waharoa, 6 km north of the trial. Twenty woven plastic 17 L bags were also filled with this vermicast mix and stored, shrink-wrapped on a wooden pallet with the other vermicast bags for convenience in case extra vermicast was required during application.

In Season 3, partially empty bags left over from Season 1 and 2's applications were used up by dividing the partial bags into the buckets used to apply vermicast to the plots.

5.4.1.2 Chicken litter

In each season, 1 t of chicken litter (enough for one season with excess) was donated annually from various broiler farms in the Waikato region of New Zealand. Different farms supplied litter each season because it is only able to be collected when sheds are emptied and the timing did not work out with the same farm each year. In Season 1, the chicken litter was collected in October 2022 and stored in a lidless, plastic-lined crate in a shed on the Matamata site until used. In Season 2, the chicken litter was collected in August 2023 and stored in the Matamata shed in a woven plastic 1 t bag, with the sides wrapped in shrink wrap, but the top unwrapped to allow the litter to breathe. In Season 3 the chicken litter was collected in August 2024 and stored in 4x 1100 L plastic wheelie bins in the Matamata shed with the lids partially propped open.

5.4.2 Treatment application

5.4.2.1 Vermicast application

To ensure even coverage, each plot was divided into eight 1.74 m x 10 m sections, and the total amount of vermicast for each plot (174 kg for 12.5 t FM/ha and 348 kg for 25 t FM/ha treatments) were divided into these eight sections. A tractor, towing a flat deck 'onion' trailer with bags of vermicast on it, was driven onto the field, along the tram lines, in the case of pre-sown crops, or next to the plot area for potato crops. In Trial A, Season 1 (onions), the misplaced tram line was used, but did not cause damage to the onions as the tractor and trailer were high enough to straddle the young onions.

21.75 kg of vermicast was weighed into 40 L plastic buckets. The buckets were ferried to the appropriate plot by wheelbarrow. The vermicast in the wheelbarrows was spread by hand, evenly on the ground surface within the marked area for the two vermicast treatments. Where crops were pre-sown, only wheel tracks and buffer zones were walked on/had wheelbarrows pass through to avoid damage to the seed beds.

5.4.2.2 Chicken litter application

Chicken litter was applied to the plots in a similar manner to the vermicast treatments. To ensure even coverage, each plot was divided into four 3.48 m x 10 m sections, and the total amount of chicken litter for each plot (41.8 kg for a rate of 3 t FM/ha) was divided into 16 buckets. Each bucket contained 10.4 kg chicken litter. Each of the four replicate plots would receive four buckets. In Season 1, a ute, carrying the pre-weighed chicken litter, was driven onto the field, along the tram lines, in the case of pre-sown crops, or next to the plot area for potato crops. The chicken litter was spread evenly by hand. In Seasons 2 and 3, the pre-weighed chicken litter was transported to the plots on the tractor with the vermicast and spread at the same time.

5.4.2.3 Notes for treatment application

Table 5-6: Sowing and vermicast/chicken litter application dates for all three seasons.

		Date of application/sowing		
		Trial A	Trial B	Trial C
Season 1	Crop	Onion	Potato	Maize
2022-2023	Vermicast	18/10/2022	29/10/2022	14/10/2022
	Chicken litter	27/10/2022	01/11/2022	20/10/2024
	Sowing	04/08/2022	03/11/2022	12/10/2022
	Harvest	02/03/2023	24/07/2023	20/04/2023
Season 2	Crop	Potato	Maize	Onion
2023-2024	Vermicast	08/12/2023	14/11/2023	24/08/2023
	Chicken litter	08/12/2023	22/11/2023	25/08/2023
	Sowing	09/12/2023	12/10/2023	18/08/2023
	Harvest	25/09/2024	15/04/2024	08/03/2024
Season 3	Crop	Maize	Onions	Potato
2024-2025	Vermicast	07/11/2024	07/08/2024	14/11/2024
	Chicken litter	07/11/2024	07/08/2024	14/11/2024
	Sowing	29/10/2024	26/07/2024	15/11/2024
	Harvest	16/03/2025	14/02/2025	23/05/2025

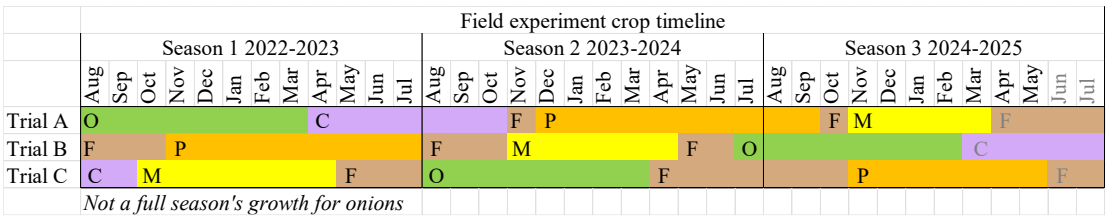


Figure 5-3: Crop rotation schedule for Trials A, B and C over the three-year trial period. Coloured sections indicate the period crops were in the ground from sowing to harvest. Green sections indicate onions; orange, potatoes; yellow, maize; purple, Persian clover/other cash crop e.g. Italian ryegrass and brown, fallow (periods where no crops were in the soil).

Table 5-6 reports the sowing and trial harvest dates, as well as application dates of vermicast and chicken litter. The length of time the crops were in the ground is also presented in Figure 5-3. In most cases, the treatments were applied close to sowing, except for Season 1, Trial A, where the onion crop had been sown in the first week of August

2022, prior to the experiment beginning on 18/10/2022. The chicken litter treatment was applied to Trial A on 27/10/2022. In Season 1, chicken litter treatments were applied later than the vermicast treatments as it was not practical to apply it at the same time. In Seasons 2 and 3, the process for chicken litter application was optimised, enabling applications close to, or on the same date as vermicast application.

5.4.3 Sampling and analysis

Where "designated sampling area" is mentioned, this refers to Table 5-7.

To avoid edge effects, sampling (of soil and crops) was restricted to an area at least 1 m in from each edge of the plots for all seasons and all crops. The length of the sampling area decreased each season and depended on the crop in place Table 5-7. For the potatoes, a larger buffer zone was used for the length, given that a proportionally larger amount of soil drag was expected during planting, which occurred after vermicast/chicken litter application. The maize sampling area was restricted to 10 m.

Table 5-7: Crop sampling areas by season and trial. Note that the beds indicated below are for sampling the actual crops. Soil samples were taken within the same *length* as the crop, but within 1 m of the *sides* of the plots.

		Trial A	**Trial B**	**Trial C**
Season 1	Crop	Onion	Potato	Maize
2022-2023	Sampling area	2 central beds x 18 m	3 central beds 7 m	7 central rows x 10 m, starting 1 m in
Season 2	Crop	Potato	Maize	Onion
2023-2024	Sampling area	3 central beds x 7 m	7 central x 10 m, starting 5 m in	2 central beds x 12 m
Season 3	Crop	Maize	Onions	Potato
2024-2025	Sampling area	5 central rows x 10 m, starting 5 m in	2 central beds x 6 m	3 central beds x 7 m

The sampling area for each trial was decreased each year, as it was assumed that soil drag would contribute to dilution of the previous treatments and would mask any potential medium-term effect of annual reapplication.

5.4.3.1 Soil samples

5.4.3.1.1 Collection

Two batches of soil samples were taken per crop, per growing season. The first was taken before the application of treatments, although base fertiliser application and sowing may have already occurred depending on the crop and the growers' schedule. The second was taken close to the harvest date.

Baseline soil samples were collected to a depth of 150 mm using a simple soil corer. All soil samples collected after the initial baseline samples were collected with a

100 mm bucket sampler. As the soils are cultivated and the topsoil is mixed at least twice per year, the discrepancy in soil core depth was not considered an issue for this experiment. At each sampling event, twenty cores were taken randomly from each plot, but within the designated sampling area (Table 5-7). Note that soil samples were taken within the same *length* as the crop, but within 1 m of the *sides* of the plots, i.e. from a wider area than the crop samples. Soil samples were stored in unsealed plastic bags, with the tops rolled down to allow the samples to air dry before sieving to 2 mm and storing prior to analysis.

5.4.3.1.2 Specific crop notes

For the onion crops, soils were sampled post-sowing. Note that the baseline samples for Season 1, Trial A were taken two months after the crop was sown as this was when the experiment began. Five cores were taken from each of the four beds, avoiding wheel tracks, but within the designated sampling area. Soil samples were also taken in the same manner after the commercial harvest (as onion bulbs were in the way of sampling).

For the potato crops, soils were sampled between power harrowing and treatment application which occurred just before sowing. At this stage, there were no formed beds and the soil was very soft. Twenty soil cores were taken at random locations within the designated sampling area. To collect a core, the soil was compacted first by pressing the ground with a boot where a sample was to be taken. Soil cores were also taken the day before harvesting within the same designated sampling area, but excluding the 3 x 1 m strips where potatoes were to be sampled from. The samples were taken from the tops of the potato beds, not directly above potato plants (visible from where stems came out of the soil as potato tubers would have been damaged). Four samples were taken from each of the five middle potato beds.

For the maize crops, 20 soil cores were taken from the designated sampling area, avoiding planting rows where seeds/seedlings and fertiliser seams were sown. The same process was followed after the crop had been commercially harvested.

5.4.3.1.3 Soil analyses

A total of 288 soil samples were collected throughout the three-year trial period. Soils were stored until analysis in October-November 2025. A 50 mL subsample of each sieved, air-dried soil sample was taken for pH and nutrient content analyses. Only pH was analysed for each soil sample. The baseline soil samples from Trials A-C in Season 1 (n = 48) were analysed individually for nutrient content via Inductively Coupled Plasma

Mass Spectrometry (ICP-MS). These were analysed as per Section 5.4.3.1.3.5 to determine soil heterogeneity. As the Latin Square trial design satisfactorily managed the heterogeneity found, no further ICP-MS analysis was necessary.

5.4.3.1.3.1 Soil pH

Soil pH was determined for each sample following Blakemore *et al.* (1987) for pH in H_2O where 10 g soil was mixed with and then extracted in 25 mL distilled water overnight before testing with a calibrated pH probe.

5.4.3.1.3.2 Soil nutrients

Soil nutrients were determined using an Agilent 8900 Inductively Coupled Plasma – Mass Spectrometer (ICP-MS; Agilent Technologies, Santa Clara, California, USA) controlled by MassHunter Workstation (version 4.5). Samples were first dried at 50 °C for one week and ground in a ball mill grinder (a Retsch Mixer Mill MM 400) at 27.5 Hz for 60 seconds. Approximately 0.2 g of the ground samples were pre-digested overnight in reverse aqua regia (3:1 concentrated HNO_3: HCl) before digestion in a water bath set to 90 °C for 1 hour. Digests were then topped up to 50 mL with Type 1 water before a 15 mL subsample was filtered through a 0.45 µm filter. The subsamples were diluted 100x by taking 0.1 mL filtered digest, adding 9.7 mL Type 1 water and 0.2 mL HNO_3 to achieve a 2% HNO_3 concentration in the sample prior to analysis for Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, P, Pb, S, Sr, Tl, U, V, Zn.

For the Baseline soil samples, a post-hoc statistical analysis was performed to confirm homogeneity of treatment plots prior to the start of the three-year trial. ICP-MS results for Na, Mg, Ca, P, Mn, Fe and Cu were analysed. Elements B, K, S, Co, Zn, As, Cd, Tl and U were below detection limits and excluded from the statistical analysis. Elements Al, V, Cr, Ni, Sr, Ba, Hg and Pb are not considered essential plant nutrients and were excluded from the statistical analysis.

5.4.3.1.3.3 Soil C:N

Soil C:N was tested on the Baseline and final soil samples for Trial B. From the remainder of the subsample ground for ICP-MS analysis, a minimum of 2 g was submitted to Lincoln University for C:N analysis. Total carbon and nitrogen were analysed using an Elementar Vario-Max CN Elemental Analyser (Elementar GmbH, Hanau, Germany). The sample was combusted at 900°C in an oxygen atmosphere. The combustion process converts any elemental carbon and nitrogen into CO_2, N_2 and NO_x. NO_x are subsequently reduced to N_2. These gases were then passed through a thermal conductivity cell to

determine CO_2 and N_2. Results were reported in elemental % as received. As DM was not tested directly on the C:N samples due to small sample sizes, a range of similarly treated samples were tested for DM and found to be 90% DM on average. This DM content was used to calculate C and N contents as %DM.

5.4.3.1.3.4 Soil Olsen P

Olsen P was tested on the Baseline and final soil samples for Trial B. A standard Olsen P extraction method from Lincoln University was used. This method follows the ISO 11263 method[7] and uses activated carbon to absorb any coloured soluble organic matter or organic P that could interfere with the development of the molybdenum blue coloured complex for determining the final P concentration.

For each sample, 1 g ± 0.05 g of air-dry, <2 mm sieved soil and 0.2 g activated carbon were weighed into a 50 mL falcon tube (centrifuge tube). A fresh extractant of 0.5 M sodium hydrogen carbonate ($NaHCO_3$) (with 1 mL 0.2% Superfloc/L) was adjusted to pH 8.5 dropwise with 6 M NaOH. Three blanks were included. Twenty millilitres of extractant was added to each tube before shaking on an end over end shaker for 30 minutes. Samples were centrifuged at 2000 rpm for 10 minutes before immediate filtering through Whatman Number 42 filter paper into 30 mL vials. Samples were frozen before sending to Lincoln University for analysis on a SMARTCHEM 200 (AMS, Frepillon, France) fully automated, direct read, bench top, discrete analyser. The applicable range is from the minimum detection limit 0.020 to 1.200 mg P/L.

Olsen P content was calculated by:

$$P\ (\mu g/g\ ) = \frac{\mu g/mL - blank\ x\ 20}{soil\ weight}$$

5.4.3.1.3.5 Statistical analysis

The baseline (pre-application, Season 1) soil data were analysed using RStudio 2025.05.1 Build 513. Levene's test for homogeneity of variance and analyses of variance (ANOVA) were performed on each nutrient analysed by ICP-MS. Trials A, B and C were compared (n = 16 plots per trial). Within each trial, spatial homogeneity was assessed by comparing rows (n = 4 plots per row) and columns (n = 4 plots per column). Finally, plots assigned to the four treatment groups (n = 4 plots per treatment) were compared within

[7] ISO 11263:1994: Determination of phosphorus. https://www.iso.org/standard/19241.html. Phosphorus levels are determined via the reaction of ortho-phosphate with molybdenum and antimony in an acid medium to form a phosphor-antimony /molybdenum complex, which is reduced with ascorbic acid to form a blue colour; the absorbance is measured at 880 nm. (Adopted from Murphy & Riley method).

each trial to confirm balanced baseline conditions. Elements were considered homogeneous when both ANOVA and Levene's test indicated no significant differences in means or variances ($p > 0.05$), respectively. Tukey's Honest Significant Difference (HSD) post-hoc tests were conducted to identify specific pairwise differences where ANOVA indicated significant variation. The same statistical analysis was performed on pH data for the Baseline soil samples.

Treatment effects on soil pH were analysed across all trials combined, with no distinction made between crops or trial location. One-way ANOVA with Tukey's HSD post-hoc test ($p < 0.05$) was applied at each sampling point.

Changes in soil parameters (C%, N%, C:N, Olsen P and pH) between baseline (Season 1) and final (Season 3) sampling were analysed. Normality and homogeneity of variance were assessed using the Shapiro-Wilk test, Levene's test and diagnostic plots. Only C% met ANOVA assumptions and was analysed using a two-way mixed ANOVA (Season × Treatment) with Fisher's LSD post-hoc. All other parameters were analysed using Wilcoxon signed-rank (seasonal change) and Kruskal-Wallis tests (treatment effects), with Dunn's post-hoc (Bonferroni correction) where significant.

5.4.3.2 Vermicast and chicken litter samples

5.4.3.2.1 Collection

Vermicast and chicken litter were sampled on the day of application for each trial, each season. Nine samples were collected in total from the three trials over the three seasons. A representative subsample was collected for analysis by taking a small sample of vermicast approximately every 20 kg spread. The sampled vermicast was double bagged in sealable plastic bags, then stored in polystyrene boxes until analysis.

A sub sample of chicken litter was taken from each pre-weighed bucket, triple bagged in sealable plastic bags and frozen at the end of the day until analysis.

5.4.3.2.2 Analysis

Vermicast and chicken litter samples were analysed for dry matter (DM), pH, electrical conductivity (EC), ash content/volatile solids, nutrient content and C:N. Each of the nine samples (one sample per trials per year) was analysed separately for pH, EC, dry matter and ash content/volatile solids. Samples were bulked by season for C:N and nutrient analyses. Vermicast and chicken litter samples were homogenised by hand before subsampling and analysis.

5.4.3.2.2.1 Chicken litter/vermicast dry matter

Dry matter was determined by oven drying approximately 25 g vermicast and 120 g chicken litter at 105 °C for three days.

$$DM = \frac{dry\ mass}{field\ moist\ mass}$$

5.4.3.2.2.2 Chicken litter/vermicast pH and electrical conductivity

Vermicast and chicken litter pH and EC were determined in a 1:5 extraction. A 10 ± 0.05 g field moist sample was shaken in 50 mL distilled water for 1 hour on an end-over-end shaker (1 revolution per second). A Eutech pH700 meter, calibrated to three points, was used to determine pH immediately after shaking. A calibrated Milwaukee MW 301 PRO EC meter (range 0-1990 µS/cm, equivalent to 0-1.9 dS/m) was used to determine the vermicast EC. The chicken litter extracts had high EC readings, so a calibrated Milwaukee MW 301 PRO High Range EC meter (range 0.0-10.0 mS/cm, equivalent to 0.0-10.0 dS/m) was used to determine EC after dilution by a factor of 3 with distilled water and then back calculated to give a final EC reading.

5.4.3.2.2.3 Chicken litter/vermicast ash content/volatile solids

For vermicast, ash content was determined by oven drying a ~5 g sample at 105 °C until the mass was stable. The mass of the sample was recorded to 0.001 g and placed in a muffle furnace set to 550 °C for four hours. The remaining ash was weighed to 0.001 g and ash content/volatile solids determined by:

$$Ash\ content = \frac{ash\ mass}{dry\ mass}$$

$$Volatile\ solids = 100\% - ash\ content$$

For chicken litter, the same method was followed, but the subsample was blended in a high-speed laboratory blender for 10 seconds before drying and weighing to produce a more even sample for ash analysis.

5.4.3.2.2.4 Chicken litter/vermicast nutrient content

The soil nutrient analysis method was used for bulked chicken litter and vermicast samples (one sample per season). See Section 5.4.3.1.3.2.

5.4.3.2.2.5 Chicken litter/vermicast C:N

The soil C:N analysis method was used for bulked chicken litter and vermicast samples (one sample per season). See Section 5.4.3.1.3.3.

5.4.3.3 Crop samples

5.4.3.3.1 Onions

The date of the onion crop lifting was determined by the growers – when 80-100% of the crop leaves had fallen over. The onions required lifting (bulbs broken away from the roots and left on the surface to dry) at least 10 days before commercial harvest. Given the scale of the experiment, and the need to work with the growers to ensure the experiment did not adversely affect commercial harvest schedules or crop quality, the onions were lifted by a two row Top Air onion harvester (a PTO-driven wheel with paddles suspended over the onion beds). The wheel gripped and pulled the onions up, breaking off the roots at the base of the bulb without damaging the bulb, as it ran over them. This resulted in movement of onions from their original position, estimated at 1 m maximum. Refer to Table 5-7 regarding designated sampling area, as this was accounted for in the sampling design. The day before subsampling the onion crop, the two central beds in each plot were split into twenty 1 m^2 subplots, by measuring out each 1 m section and shuffling onions to either side of the 1 m line.

5.4.3.3.1.1 Pre-harvest

In Season 1, there was 18 m^2 of potentially harvestable onions in each plot. A total of 11 m^2 per plot were analysed for bulk yield (kg/m^2) and density ($onions/m^2$). An a priori power test using G*Power Version 3.1.9.7 was conducted to determine the number of onions needed to detect a statistically significant difference in average onion mass between the treatments. Means from a pilot trial conducted on the same variety of onions from the year prior were used. The means were 117.1 and 125.6 g/onion, both with equal standard deviations (SD), $\alpha = 0.05$ and power >0.80. The standard deviation was adjusted as part of a sensitivity test. It was determined that at least 220 onions per plot were required. Based on this information, it was determined that 3 x 1m^2 subplots would need to be individually analysed.

The 1 m^2 subplots within the designated sampling area were given a number from 2-19 in Season 1, 5-16 in Season 2 and 8-13 in Season 3. The "=RANDBETWEEN()" function in Excel was used to generate 11 random numbers associated with the 1 m^2 subplots for sampling, with 5 or 6 subplots from each of the two central beds. Three of these subplots were then randomly selected for detailed analysis (individual onion size and mass).

5.4.3.3.1.2 Trial harvest (sample collection)

All the onions in each 1 m^2 subplot assigned to be sampled were counted and bagged in open-weave plastic onion storage bags. Rotten onions were recorded separately and not bagged. Bagged onions were stored in the canopy of a ute/pickup truck before being transported to the Matamata shed for temporary storage on pallets for up to two weeks before analysis. Except for three bags of onions from the Season 1 plots, each bag of onions was weighed in bulk on the experiment harvest day.

After sampling the onion crop, the plot markers were removed for the commercial harvest. After the commercial harvest, the plots were remarked and post-harvest soil samples collected as per Section 5.4.3.1.

5.4.3.3.1.3 Yield and size data collection

Two sets of data were generated for statistical analysis: bulk and individual data. Of the 11 bags sampled from the field, 8 bags from each plot were discarded once their yield (kg onions/m^2) and number of onions in the bag (onions/m^2) had been recorded (this formed the "bulk" dataset). Over three days, one bag of onions per plot was processed separately. For these three bags per plot, each onion was cleaned by cutting the stem 1 cm from the bulb and removing loose leaves and dirt clumps. For each onion, its size class was determined using sizing rings appropriate for the variety (<40 mm = pickling, 40-60 mm = small, 60-80 mm = medium, >80 mm = large). Individual mass was measured using a precision balance (Radwag® WTC 2000, WL-210-0001; readability 0.01 g). These measurements formed the "individual" dataset. In Season 1, masses were manually recorded. In Seasons 2 and 3, data were recorded electronically via a laptop connection using RAD key software (version 1.1.0.7).

5.4.3.3.1.4 Statistical analysis for yield data

Data was analysed using RStudio 2025.05.1 Build 513. As sampling was the same between seasons, the same tests were performed for each of the three years. Data were tested for normalcy using Q-Q plots and Shapiro-Wilk tests. Analyses of variance (ANOVA) blocked by row and column factors were carried out on the data for average treatment yield and density. ANOVA were also performed on the proportion of onions (count and mass) for each size class (pickling, small, medium and large). Levene's test was used to assess the assumption of homoscedasticity for the ANOVAs. Post-hoc Fishers least significant difference tests were performed on statistically significant findings.

Spatial analysis was also performed on the data, to determine whether environmental factors were influencing results.

A multi-season analysis was conducted to determine whether there was a detectable medium-term effect of the treatments on onion yield, density and individual size and mass. Data were tested for normalcy before type III ANOVA. Bonferroni correction was applied to post-hoc Fishers LSD tests when ANOVA effects were statistically significant ($p > 0.05$).

A post-hoc power test was performed for the seedling emergence data using G*Power (version 3.1.9.7). A one-way ANOVA ($\alpha = 0.05$) and observed effect size (Cohen's f) were used to determine achieved power. An a priori analysis ($1 - \beta = 0.80$) was then performed with power to determine the number of replicates required to detect a significant difference.

5.4.3.3.1.5 Cost-benefit analysis

A cost-benefit analysis was performed based on the significant benefit of applying vermicast at 25 t FM/ha to onions in Season 3. The analysis included costs of purchasing, transporting and spreading the vermicast as well as farmgate profit for onion yield. Prior to analysis, the yields for the Control and 25 t FM/ha vermicast, reported in kg/m^2, were converted to t/ha by dividing by 1.75 m (width of one onion bed + one wheel track) and multiplying by a factor of 10. The MyNoke retail price of $29.95 for bulk vermicast was used. Industry estimates of costs for transport profit were used (Eamon Balle, personal communication, March 27, 2026). The cost of bulk transport was estimated at between $20-25/t (for a 62 km one-way trip). An intermediate $23/t value was used. Spreading cost was estimated at $6/t. A farmgate profit of $250/t onions was used, based on estimates of an average yielding crop in an average year. All costs/prices excluded GST. Sensitivity analyses were performed to understand what factors were most important for overall profit and what the minimum yield increase would need to be to turn a nominal profit of at least $200/ha. Refer to Appendix 4: Season 3 onion cost-benefit analyses.

5.4.3.3.2 Potatoes

The date of the potato harvest was determined by the growers. In each season, near the end of the potato crop growth period and prior to harvest, a desiccant was sprayed over the remaining foliage. This was to kill-off the shoot and stop the potato plants from growing and make the crop easier to harvest.

The timing of the trial harvest depended on the moisture content of the soil to minimise soil sticking to the tubers during sample collection. Going into cooler, wetter

months leading up to the harvest, site checks and weather forecasts were used to determine the most suitable date for the trial harvest, prior to the commercial harvest.

5.4.3.3.2.1 Pre-harvest

The day before the trial harvest, three 1 m strips were pre-marked in each plot (see Table 5-7 for designated sampling areas). When marking each 1 m strip, the first marker was placed between two plants. Plants were identified by groups of dead stems in the beds. This was to minimise the number of partial potato plant samples. Soil samples were taken as per Section 5.4.3.1 from within the designated sampling area, but excluding the marked 1 m strips, to avoid damaging the tubers.

5.4.3.3.2.2 Trial harvest (sample collection)

At the trial harvest, all tubers within each 1 m section were dug up and the soil removed from them by dry brushing. Tubers were grouped with their original plant. This was done by identifying the basal end of the tuber and the group of stems it pointed towards as they were being dug up. The basal end was identified by locating the proximal point of attachment to the stolon i.e. where the thick stolon connected to the tuber. For potato tubers found crossing the boundaries of the 1 m section, if more than half the tuber sat in the 1 m section, it was included in the sample.

5.4.3.3.2.3 Yield and size data collection

All yield data were collected in the field where the potatoes were grown.

Where some tubers from a sample plant were outside the 1 m section, this plant was recorded as a partially sampled plant. Rotten tubers were recorded but not measured for size or mass.

For each plant sampled, all tubers were passed lengthwise through circular sizing rings with the following internal diameters: <40 mm = unmarketable, 40-50 mm = small, 50-60 mm = medium and >60 mm = large. For example, to be classed as ‘medium’, a tuber had to be able to pass lengthwise through the 60 mm ring, but not the 50 mm ring. The number and bulked mass of tubers in each size class for each plant was recorded. Bulked mass was measured using a battery-powered precision balance (Radwag® WTC 2000, WL-210-0001; readability 0.01 g). In Season 1, masses were manually recorded. In Seasons 2 and 3, data were recorded electronically via a laptop connection using RAD key software (version 1.1.0.7). For cases where the mass of tubers for a size class exceeded the balance’s maximum weight, split measurements were taken and manually added together.

Approximately 15 kg of large potatoes (randomly subsampled from the three 1 m sections per plot) were bagged in woven white plastic bags and collected at the end of the day. All other potatoes were discarded.

In Season 3, although the tubers were harvested and brushed, there was not enough time to size and weigh the tubers from Plot C3, C2 or any of Row D on the day. Instead, all the bagged tubers from these plots were taken, along with the large potatoes subsampled from each plot and transported to the Waharoa storage facility and kept in a 9 °C chiller unit overnight. Size and mass data was collected on these plots the following day, as well as 15 kg large tubers per plot being kept aside for specific gravity and fry testing.

5.4.3.3.2.4 Specific gravity (quality testing)

In Season 3 only, after four days of storage in the chiller unit, specific gravity was measured using the growers' equipment and methods for commercial measurement. A weighstation (readability 0.005 kg) balance sat on a shelf with a wire basket hooked suspended from the balance. The basket was on an adjustable chain that was long enough for the basket to be fully submerged in a sink filled with water directly below the balance. The scales were tared with the basket out of the water. For each plot, the basket was filled with an average of 9 kg of potatoes. The fresh mass of the potatoes was recorded. The basket was then submerged and the new mass recorded. Specific gravity was then calculated using:

$$Specific\ gravity = \frac{fresh\ mass}{(fresh\ mass - wet\ mass)} \quad (1)$$

5.4.3.3.2.5 Fry testing (quality testing)

Except for a two-hour period where all the potatoes in storage were removed from the chiller to sort samples for processing, five of the largest remaining potatoes were selected from each plot for fry testing after six days storage in the chiller unit.

Each of the five potatoes was processed in sequence to the frying stage. For each potato, a 2 cm lateral section was cut out of the centre. This section was then placed in a Hobart VPU vegetable slicer, set to cut 2 mm slices. Where the diameter of the potato was too large to fit inside the slicer, a small section was cut off the side of the potato section. The entire section was sliced. One 2 mm slice was selected from the centre of the slices produced and immediately rinsed in a bucket of tap water to remove starch while the remaining potatoes were sectioned and sliced. Once all five 2 mm slices were ready, they were rinsed under running water and the edges scrubbed gently to remove any

remaining soil. The slices were blotted with a cotton towel to remove the majority of the water and then blotted with a fresh paper towel. The five slices were laid flat in a frying basket and fried at 180 °C for three minutes the chips were flipped halfway through cooking. Frying was done in eight litres of fresh canola oil in a Roband Frypod FR28 that had been preheated for two hours prior to frying the first sample. After frying, the chips were stood upright in the wire basket to drain for a few minutes as they cooled and were then transferred to a plastic dish. The remaining oil was blotted off with a paper towel before the five chips were placed on a white background in a photo box with a colour tile and a picture taken with the flash setting on an iPhone 12 mini. Each chip was then placed on a white tile and individually assessed for colour using a Konica Minolta Chroma Meter CR-410 set in L*a*b* colour space using CIE standard illuminant C. Illuminant C is not the most modern illuminant to use – D65 is, but this was not available on the chromameter. The L*a*b* values were then converted to RGB (Appendix 6: L*a*b* to RGB conversion) and the percent whiteness calculated using:

$$\text{Percent whiteness} = \frac{(R + G + B)}{765} \times 100 \quad (2)$$

5.4.3.3.2.6 Statistical analysis

Potato yield and size distribution data were analysed at the plot level. Individual plant data were aggregated to plot totals, and yield expressed as kg/m². This was based off a sampled strip area of 2.61 m² (3 m × 0.87 m) per plot. Tuber density was expressed as tubers/m^2. Average tuber mass was calculated as total plot mass divided by total tuber count. Column D data was incomplete in both Seasons 1 and 3 so the full 4×4 Latin Square design could not be used. Instead, a randomised complete block design with Column as the blocking factor (n = 3) was used. Treatment effects were tested using one-way ANOVA with Column as a covariate. Normality of residuals was assessed using the Shapiro-Wilk test, assessing residual plots and homogeneity of variance using Levene's test. Where a significant treatment effect was detected, treatment means were compared using Fisher's LSD test with Bonferroni correction ($\alpha = 0.05$). For non-significant results, effect sizes (Cohen's f) and post-hoc statistical power were calculated using G*Power (version 3.1.9.7).

In Season 3, mass data for undersized, small and medium tubers from one plant in plot B2 (12.5 t FM/ha vermicast treatment) were not recorded. Count data for all size classes and mass data for large tubers were collected for this plant. Plot-level mass

variables for B2 were calculated from the remaining 15 plants, resulting in a minor underestimation of mass in the undersized, small and medium size classes for this plot.

Treatment effects on specific gravity and whiteness were tested using one-way ANOVA. For whiteness, plot means were calculated from five subsamples per plot prior to analysis. Assumptions of normality and homogeneity of variance were assessed using the Shapiro-Wilk test and Levene's test respectively, and residual diagnostic plots were inspected. Where treatment effects were significant, pairwise comparisons were made using Fisher's LSD with Bonferroni correction.

5.4.3.3.3 Maize

The date of the maize crop harvest was determined by contractors and not the growers. In Seasons 1 and 2, the maize crop was destined for grain so harvesting was late in the season, allowing the grain to dry. On average, the rows for these crops were planted 0.5-0.6 m apart. In Season 3, the maize crop was destined for silage. The crop was also harvested earlier than the previous seasons, when the grain was wetter. The rows were planted 0.75-0.8 m apart. In all years, the trial harvest was left as close to the commercial harvest as possible.

5.4.3.3.3.1 Trial harvest (sample and data collection)

Depending on the season, for each plot, a 5-7 row wide x 10 m long rectangle was marked out, as described in Table 5-7. Ears were sampled from 100 plants. This was done by sampling 25 plants from four alternating rows within the sample area. For each of the four rows, all ears from every second plant, up to 25 plants per row were sampled. Plants usually only grew one ear, however, where a selected plant had multiple ears, all ears were sampled, but this was still counted as only 1/25 plants. Not all plants produced ears. These were still counted as 1/25 plants, even if no ears were removed. Not all plants survived to maturity – given the uniform plant spacings, it was clear where a plant would have been. Missing plants were also counted as 1/25 plants. All sampled ears were bagged in woven plastic onion bags and transported to the Matamata shed for mass and quality measurements.

In Seasons 1 and 2, the total number of living plants within the marked sampling area in maize rows 4, 6, 7, 8, and 10 were counted. In Season 3, the same was counted in maize rows 3, 4, 5, 6 and 7.

5.4.3.3.3.2 Sample processing

Maize kernels were stripped from each cob and weighed separately using a precision balance (Radwag® WTC 2000, WL-210-0001; readability 0.01 g). In Season 1, masses were manually recorded. In Seasons 2 and 3, data were recorded electronically via a laptop connection using RAD key software (version 1.1.0.7). All kernels from one plot were homogenised after weighing. For each plot, two representative 2 L sub samples of the mixed maize kernels were taken and stored in two layers of sealable plastic bags. Half of these were submitted to Hill Laboratories for feed quality analysis using Near Infra-Red Spectroscopy (NIRS). The other half was taken back to The University of Waikato for FM and DM analysis.

In Season 1, the maize ears were stored in the onion bags on wooden pallets in the shed on the Matamata site for three weeks as there was a delay in the arrival of the threshing machines used to strip the kernels off the cobs. During this storage period, grain from some ears were eaten by rats. To prevent this in the future, a rat bait station was installed in the shed for the remainder of the trial. Maize samples were also processed closer to the sampling date in Seasons 2 and 3.

In Season 3, the grain was much wetter than the previous seasons, so processing took much longer, and storage was altered. Processing took four days with one sampled Column being processed per day. Cobs dried noticeably during storage, despite efforts to maintain moisture (e.g. bagging to limit drying). After threshing the kernels from the cobs in one Column, the husks and silks from the next Column were removed. The cobs with the kernels still attached were replaced in the onion sacks and then stored in a woven white plastic 1 tonne bag, with the top tied, overnight to reduce moisture loss as this was anticipated to occur faster without the husks and silks. After subsampling the kernels, the quality subsamples were double bagged and frozen at The University of Waikato. The FM and DM subsamples were double bagged and refrigerated at The University of Waikato until all the samples in Matamata had been threshed.

For each season, a 100-kernel subsample was needed from each plot for FM and DM analysis. The kernels in the 2 L subsample for each plot were tipped into a tray and homogenised. The kernels were then poured over a wooden board with 100 holes drilled in it, each approximately 10 mm diameter and 10 mm deep. The chaff was blown off and the selected kernels were examined. Where two kernels were in one hole, the uppermost one was removed. Any kernel that was damaged (cracked by the threshing process) was replaced with another randomly selected (but whole) kernel. The kernels were then

weighed in an aluminium tray and dried at 60 °C for five days and reweighed after cooling. The DM_{60} content at was calculated from the FM and DM_{60} of the 100 kernels per plot.

$$Dry\ matter\ content\ (DM_{60}) = \frac{Dry\ matter}{Fresh\ matter} \times 100 \quad (3)$$

Maize quality analysis was conducted by Hill Laboratories. The tests performed were: organic matter digestibility (%DM), Nitrogen (%DM), dry matter (%), crude protein (%DM), neutral detergent fibre (%DM), organic matter (%DM), ash (%DM), metabolisable energy (MJ ME/kg DM), soluble sugars (%DM), Starch (%DM), crude fat (%DM) and non-structural carbohydrates (%DM). Acid detergent fibre and lignin were also tested, but as only one plot (B4, Season 3, acid detergent fibre) was reported above the default detection limit, these were excluded from the analysis.

5.4.3.3.3.3 Post-harvest

After the commercial harvest, the plots were remarked and post-harvest soil samples collected as per Section 5.4.3.1.

5.4.3.3.3.4 Statistical analyses

Yield and quality data were assessed for normality using the Shapiro-Wilk test and homogeneity of variance using Levene's test. Treatment effects were assessed using one-way ANOVA with row and column included as blocking factors within the Latin square design. Post-hoc pairwise comparisons used Fisher's LSD with Bonferroni correction where significant effects were detected for treatment, row or column. Where no significant treatment effect was detected, effect size was reported as Cohen's F. Achieved power, Type II error rate and minimum replicates required to achieve power of 0.80 at $\alpha = 0.05$ were calculated for all analysed using the pwr package in R.

Maize quality data from Seasons 2 and 3 were compared using independent samples t-tests, with Welch's t-test substituted where Levene's test indicated significant heterogeneity of variance. Normality was assessed using the Shapiro-Wilk test. All quality variables were tested with treatment ignored, giving n = 16 per season.

5.5 Results

5.5.1 Soil profiling and site history

The experiment site is located at the southern end of the Hauraki Basin, in a flat-lying area between Matamata and Waharoa townships. Although the three trials were located within 1 km of one another on the experimental site, each was on a different soil series with varying soil properties (Figure 5-4). The soil at Trial C, with a silt loam topsoil,

is a representative of the Otorohanga family (Otoro_74a.1 sibling (Manaaki Whenua, 2025c)), and is classified as a Typic Orthic Allophanic soil (Hewitt, 2010). The soil profile shows coarse volcanogenic alluvium emplaced >24,000 years ago (part of the Hinuera Formation: Manville and Wilson, 2004; Lowe and Green, 2025). The alluvium is overlaid by volcanic ash/tephra on all three sites, although this was not so obvious in the poorly drained sites (Trial A and B). The soil at Trial B, with a silt-dominated topsoil, is a representative of the Bruntwood family (Brunt5a.1 sibling (Manaaki Whenua, 2025a)), and is classified as a Mottled Orthic Allophanic soil (Hewitt, 2010). A composite tephra mantle overlies the poorly drained alluvium. The soil at Trial A, with a silt-dominated topsoil, is a representative of the Matuku family (Matu_14.2 sibling (Manaaki Whenua, 2025b)), and is classified as an Acidic Orthic Gley soil (Hewitt, 2010). Both the alluvium and the overlying tephra are poorly drained (Figure 5-5).

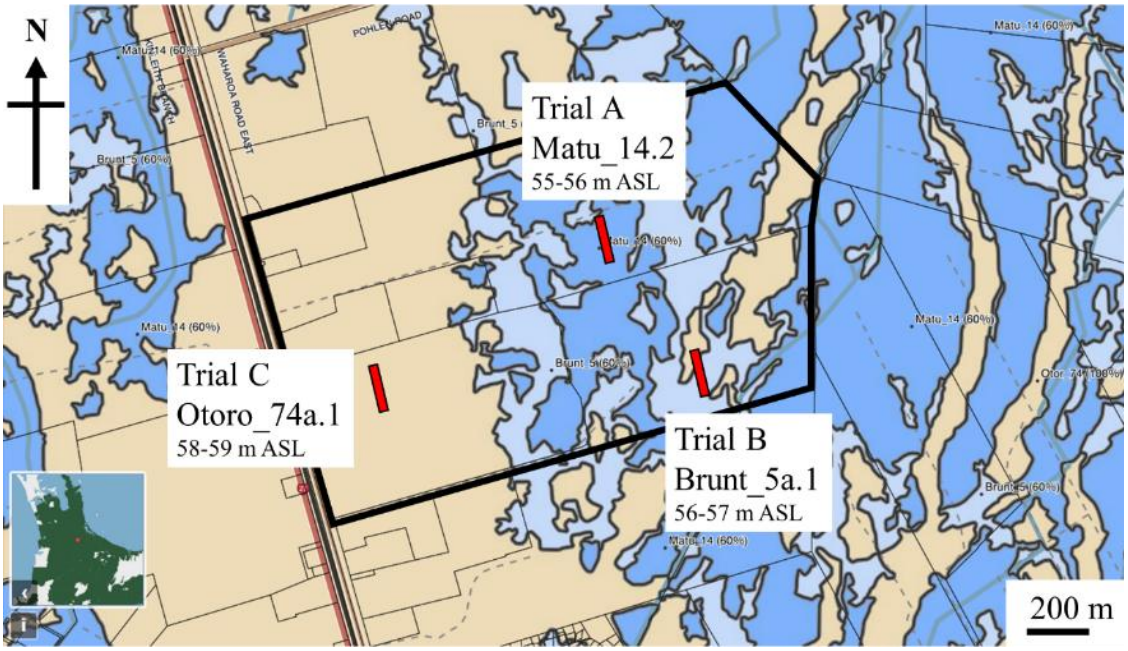


Figure 5-4 Soil map for all three trial areas A-C, identified by red boxes (to scale). Soil sibling names are provided along with elevation in metres above sea level (ASL). The boundary for the farm the trials were conducted on is outlined in black. Basemap from Manaaki Whenua – Landcare Research, 2025, https://smap.landcareresearch.co.nz.

Except for one auger in Trial A, all five augers per site indicated the presence of allophane (an aluminosilicate clay mineral), supporting the field evidence that the upper parent material is of volcanic (tephra) origin. However, the uneven layering of silt and sand also indicated a fluvial influence for the lower parent material. Three significant geological events helped shape the soils ultimately in the local landscape. The first was the reworking by the ancestral Waikato River of the huge volume of loose pyroclastic material deposited by the Oruanui super-eruption c. 25,600 cal yr BP (Manville & Wilson,

2004; Barker *et al.*, 2021) that provided the parent material of the lower part of the soil profiles. The second event was avulsion of the ancestral Waikato River away from the Hauraki Plains pathway into the Hamilton Basin about 24,000 cal yr BP (Lowe and Green, 2025; Villamor et al., 2025). This abandonment left the Hinuera Surface free to accumulate tephras incrementally over the next 24,000 years (i.e. the third geological event). These tephras form the upper parent material in many places on the alluvium (Hinuera Formation) (Villamor *et al.*, 2025).

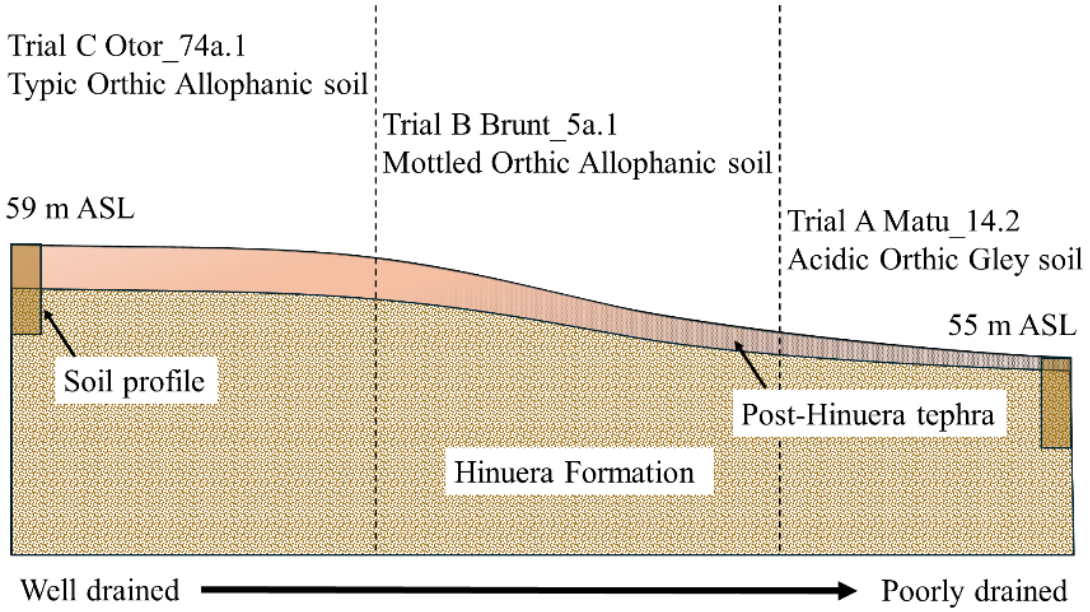


Figure 5-5: Approximate cross section of site soils (not to scale) showing soil subgroup (of Hewitt (2010)), drainage and elevation in metres above sea level (ASL) across the three trial sites on the market garden farm (all within 1 km of one another). Diagram after Villamor *et al.* (2025).

5.5.1.1 Alluvium deposition

Prior to the Oruanui super-eruption, the ancestral Waikato River was a high energy, braided system flowing north through the Hauraki Basin and into the Pacific Ocean beyond the present-day Firth of Thames (Lowe & Green, 2025). Around 25,600 cal yr BP, the Oruanui super-eruption occurred, depositing around 1,170 cubic kilometres of loose pyroclastic material and forming thick and extensive deposits of non-welded ignimbrite in the central North Island, centred on the Taupo area (Wilson, 2001; Lowe & Green, 2025). The ancestral Waikato River, still a high-energy braided system, transported unconsolidated volcanogenic alluvium from this super-eruption and deposited it in the Hauraki Plains, forming part of what is known as the Hinuera Formation. Circa 24,000 cal yr BP – about 1,500 years after the Oruanui super-eruption – the Waikato River avulsion at Piarere occurred and deposition in the Hauraki Basin

stopped. The avulsion is linked to the buildup of deposited material at Piarere which blocked the river's original pathway north at this point. Since then, the river has diverted west through the Hamilton Basin, joining the Waipa River at present day Ngaruawahia and finally emptying into the Tasman Sea at Port Waikato on the west coast (Figure 5-6).

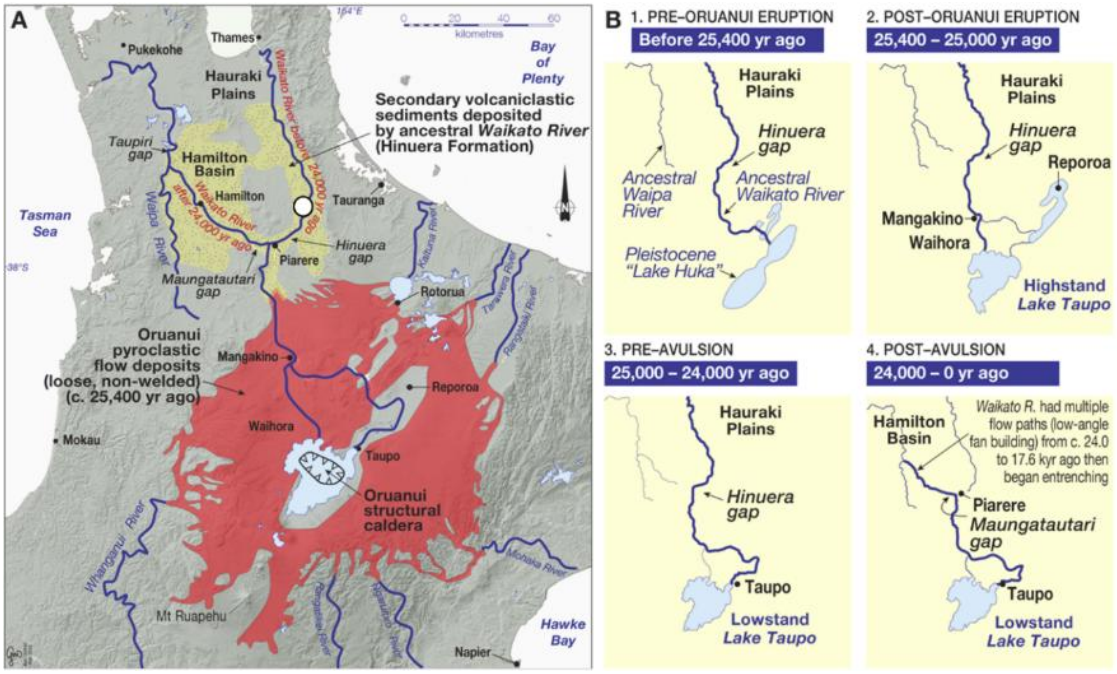


Figure 5-6: (A) Map showing the extent of the Oruanui super-eruption ignimbrite distribution (red). The approximate trial site location is marked with a white circle east of Hamilton, within the Hauraki Basin (yellow area). Secondary volcaniclastic sediments (Hinuera Formation) were later deposited in the Waikato region, including the Hauraki Basin. Diagram after Lowe (2023) and Lowe and Green (2025).

(B) Waikato River flow paths before and after the Ōruanui super-eruption (maps **1, 2**), and before and after the avulsion (abandonment of a river course, formation of a new one) at Piarere (maps **3, 4**). Diagram from Lowe and Green (2025).

5.5.1.2 Tephra deposition

Both the Oruanui super-eruption and the Piarere avulsion occurred near the end of the last Glacial Maximum, after which the climate was beginning to warm. Once the Waikato River abandoned the Hauraki Plains, leaving the Hinuera Surface, a succession of tephra beds was deposited incrementally over the next 24,000 years. During this period, the climate began to warm, and the area became reforested from soon after c. 17,600 cal yr BP (Newnham *et al.*, 1989; Newnham *et al.*, 2003; Lowe & Green, 2025). Prior to c. 17,600 cal yr BP, the landscape was primarily unforested and dominated by shrubland and grassland. In addition to the incremental tephra addition, plant succession and rapid reafforestation also influenced the soil formation processes on the alluvial plains (Newnham *et al.*, 1989).

Due to the influences of the above geological processes, many of the soils in this area are two-storied soils with an upper mantle of post-24,000-cal-yr-old tephra over lower alluvial material (Hinuera Formation). The resulting soil character is influenced mainly by drainage: very well drained (Otorohanga) to poorly drained soil (Matuku) with an intermediate moderately well drained soil (Bruntwood) (see Figure 5-5).

5.5.1.3 Recent site history

In the past few decades, the three trial sites have had similar land management histories, though the area each site was part of varies as follows. The area Trial A was part of a well-maintained, fertile dairy farm until 2012 after which it was converted into horticultural production (onions, potatoes and maize rotational cropping). Trials B and C were part of a well-maintained, fertile dairy farm until the early 1990's when it was converted into horticultural production (onions, potatoes and maize cropping rotation). In 2003, 30 ha (including Trial C) was cropped as asparagus. In 2017, the area returned to the standard onion, potato and maize cropping rotation.

5.5.2 Baseline soil analyses

Additional data are reported in Appendix 3: baseline soil analyses.

5.5.2.1 Baseline soil nutrient results

The ANOVA and Levene's test results indicated that there were significant differences in Na, P, Mn and Cu between the soils of the three trials, but not Mg, Ca and Fe (Table 5-8). This indicates that the three trials were not homogenous, despite their proximity (<1 km between sites).

Within-trial variation was present. When analysed on a column or row basis within trials (Tukey's HSD), Trial A showed Column A had a significantly higher Na concentration than B, C and D and Column D had a significantly lower Mg and Mn concentration than Column B. However, rows within Trial A were homogenous.

Trial B columns were homogenous, as were the rows, except for Cu which was significantly higher in Row 2 compared to Row 4.

Trial C had the highest variation in columns. Broadly, adjacent Columns A and B were homogenous, as were C and D for all nutrients. However, when comparing other column pairs, variation was found in nutrients. Trial C rows were homogenous.

See Table 8-4 to Table 8-9 (Appendix 3: baseline soil analyses) for averages of column and row analyses for Trials A-C.

Table 5-8: Average Baseline element concentration by Trial. ANOVA = analysis of variance.

	Average concentration (mg/kg dry soil)			p value		Tukey's Honest Significant Difference p value		
Element	**Trial A**	**Trial B**	**Trial C**	**ANOVA**	**Levene's test**	**B vs A**	**C vs A**	**C vs B**
Na	2.67	2.16	1.48	1.40E-05	0.91	0.07	0.00	0.01
Mg	4.78	3.97	4.65	0.07	0.03	0.08	0.93	0.17
Ca	46.1	47.6	48.3	0.78	1.00	0.88	0.78	0.98
P	22.7	18.3	21.1	0.01	0.52	0.01	0.46	0.13
Mn	6.68	2.98	5.4	2.00E-03	5.20E-13	$1.79x10^{-03}$	0.44	0.05
Fe	85.4	83.7	81.2	0.60	0.21	0.91	0.58	0.82
Cu	0.08	0.06	0.08	0.01	9.00E-04	0.01	0.94	0.02

Table 5-9: Average Baseline element concentrations by treatment (four plots per treatment). Samples were taken prior to treatment application. ANOVA = analysis of variance.

	Treatment average concentration (mg/kg dry soil)				p value	
Element	**Control**	**3 t FM/ha chicken litter**	**12.5 t FM/ha vermicast**	**25 t FM/ha vermicast**	**ANOVA**	**Levene's test**
Trial A						
Na	2.56	2.66	2.90	2.54	0.85	0.71
Mg	4.53	4.42	4.26	5.94	0.25	0.99
Ca	48.0	43.9	40.0	52.5	0.27	0.45
P	23.8	21.0	24.3	21.8	0.69	0.11
Mn	6.56	7.26	5.16	7.73	0.56	0.69
Fe	81.8	87.3	81.9	90.6	0.61	0.59
Cu	0.08	0.08	0.07	0.08	0.77	0.74
Trial B						
Na	2.11	2.40	1.84	2.28	0.63	0.35
Mg	4.11	4.21	3.93	3.66	0.82	0.62
Ca	51.7	45.4	46.3	47.1	0.76	0.94
P	17.3	20.5	16.7	18.7	0.45	0.37
Mn	2.20	3.91	2.68	3.12	0.48	0.95
Fe	78.1	81.0	80.4	95.31	0.34	0.92
Cu	0.07	0.07	0.06	0.06	0.50	0.61
Trial C						
Na	1.49	1.43	1.70	1.29	0.88	0.52
Mg	5.18	4.45	4.65	4.30	0.62	0.92
Ca	48.4	48.6	51.3	44.8	0.83	0.45
P	19.5	21.2	22.2	21.3	0.86	0.06
Mn	5.22	5.58	5.68	5.25	1.00	0.69
Fe	80.6	77.9	80.8	85.3	0.82	0.96
Cu	0.08	0.08	0.08	0.07	0.94	0.09

Despite spatial variation across rows and columns, no significant differences were detected among treatment groups within trials. This demonstrates that the Latin square design effectively balanced the initial soil nutrient conditions across all treatments within each trial.

5.5.2.2 Baseline pH analysis

Average Baseline pH values for the three trials were 6.38 ± 0.1 for Trial A, 6.79 ± 0.2 for Trial B and 6.63 ± 0.2 for Trial C. The ANOVA ($p = 2.77x10^{-9}$) and Levene's test ($p = 0.042$) results indicated that there were significant differences between the three trials. This indicates that the three trials were not homogenous, despite their proximity (<1 km between sites).

Within-trial variation was present. When analysed on a column or row basis within trials, Trial A rows and columns were not homogenous. Trial B columns were homogenous, but rows were not. Trial C rows were homogenous, but columns were not (Table 5-10).

Within Trial A, columns A, B and C were homogenous. Column D was homogenous with A, but not B or C. Within Trial B, only adjacent pairs of rows 1 and 2 as well as 3 and 4 were homogenous. No other row combinations were homogenous. Within Trial C all columns were homogenous, except for B and C, the adjacent centre rows. Tukey's HSD data are reported in Table 8-10.

Table 5-10: Analysis of variance (ANOVA) and Levene's test results for homogeneity of pH within trial columns and rows.

Test	ANOVA	Levene's test	Homogenous?
Trial A rows	0.374	0.041	
Trial A columns	0.007	0.001	
Trial A treatments	0.899	0.983	TRUE
Trial B rows	4.14E-06	0.016	
Trial B columns	0.817	0.200	TRUE
Trial B treatments	0.996	0.532	TRUE
Trial C rows	0.190	0.987	TRUE
Trial C columns	0.043	0.472	
Trial C treatments	0.688	0.094	TRUE

Despite spatial variation across rows and columns, no significant differences were detected among treatment groups within trials. This demonstrates that the Latin square design effectively balanced the initial pH conditions across all treatments.

5.5.3 Initial and final soil comparisons

Between the baseline and final soil samples, no changes or interactions were found for N% or C:N (Table 5-11). A significant season effect was detected for Olsen P where all treatments exhibited an equal increase in Olsen P levels. A treatment effect of pH was detected in Season 3 where the 25 t FM/ha vermicast treatment had significantly higher average pH than both the chicken litter and control treatments. A seasonal effect was detected for C% which increased overall from 3.5%-3.6% averaged across all plots

between seasons. A near-significant interaction (p = 0.058) suggests this increase may not have been uniform across treatments Figure 5-7.

Table 5-11: Assumption checks, tests selected and results for comparison of soil parameters between the baseline and final soil samples. Results are for Trial B. Statistical significance is indicated by *.

	N %DM	C %DM	C:N	Olsen P	pH
Assumption checks					
Shapiro-Wilk p value	0.139	0.076	0.146	0.346	0.012*
Levene's test p value	0.957	0.871	0.568	0.094	0.547
Test used	Kruskal-Wallis	ANOVA	Kruskal-Wallis	Kruskal-Wallis	Kruskal-Wallis
Results (p values)					
Season effect	0.124	0.003*	0.897	5.00E-04	0.134
Treatment effect (Season 1)	0.602	0.497	0.982	0.917	0.996
Treatment effect (Season 3)	0.782	-	0.544	0.963	0.019*
Interaction	-	0.058	-	-	-

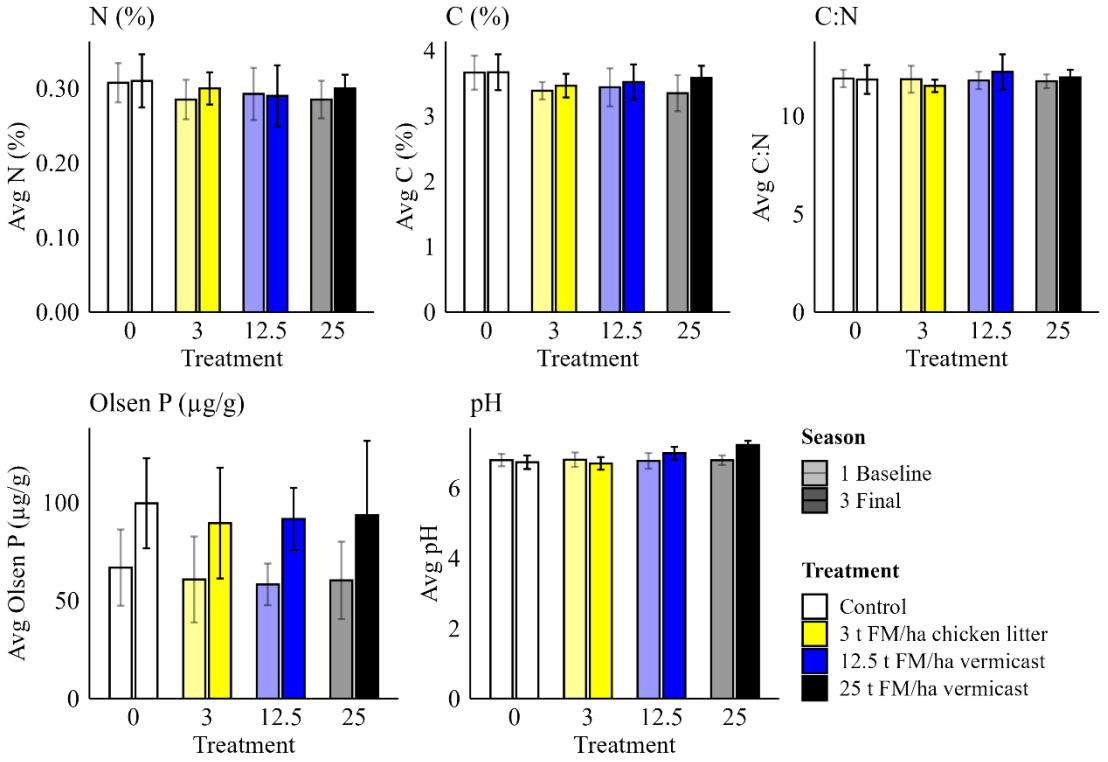


Figure 5-7: Average values ± standard deviation for comparison of soil parameters between the baseline and final soil samples. N = nitrogen, C = carbon, P = phosphorus.

5.5.4 Vermicast and chicken litter analyses

Being organic in nature, both the vermicast and chicken litter varied within and between seasons. Though the vermicast was from the same bulk batch, the dry matter fluctuated (Table 5-12), particularly in Season 1, where vermicast application rates on a dry basis for Trial B (potatoes) were almost double that for Trial C (maize). The

difference in vermicast applied on a dry matter basis in Season 1 was 4.3 t DM/ha for the lower vermicast rate and 8.5 t DM/ha for the higher vermicast rate. For chicken litter this was 0.1 t DM/ha. In Seasons 2 and 3, the DM content (48-52%) was similar between treatments. There was still a 0.5 t/ha DM difference for the lower vermicast rate and a 1 t/DM ha difference for the higher rate between applications. Chicken litter dry matter application rates also fluctuated, though to a lesser total extent than vermicast as Trial A in Season 2 received 0.1 t DM/ha more than B and C in Season 2. There was no measurable difference between trial DM application rates of chicken litter in Season 3.

Table 5-12: Vermicast and chicken litter treatment dry matter application rates per trial per season. Results are reported as t DM/ha. FM = fresh matter.

Season		**1**			**2**			**3**	
Trial	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
				Vermicast (t DM/ha)					
Dry matter content	46%	66%	32%	52%	48%	50%	49%	48%	48%
12.5 t FM/ha	5.8	8.3	4.0	6.5	6.0	6.3	6.1	6.0	6.0
25 t FM/ha	11.5	16.5	8.0	13.0	12.0	12.5	12.3	12.0	12.0
				Chicken litter (t DM/ha)					
Dry matter content	55%	52%	55%	51%	45%	48%	45%	47%	47%
3 t FM/ha	1.7	1.6	1.7	1.5	1.4	1.4	1.4	1.4	1.4

The vermicast tended to have a slightly alkaline pH (7.3-7.49). In Seasons 1 and 2, the chicken litter was more alkaline (8.29-8.87). Overall, the chicken litter pH was far more variable, especially in Season 3 with a range between 6.96 for Trial B and 9.36 for Trial A. Electrical conductivity was at least ten times higher in chicken litter compared to vermicast applied to the same trial in the same season. Ash and volatile solids contents indicate that the chicken litter had a high organic matter content; chicken litter volatile solids averaged 85% compared to 22% in the vermicast, indicating the vermicast applied had a relatively high inorganic matter content (Table 5-13).

Chicken litter and vermicast were dissimilar in elemental content (Table 5-14). Although they were tested for and found to be present in the samples, not all elements were detected above their respective quantitation limits (QL). Although their accuracy is lower than results detected above QL, these results are still reported. Vermicast was dominated by Ca, followed by Al, N, and Fe. Sulphur and potassium were detected, but below their respective QL. Magnesium was also detected. Conversely, chicken litter was dominated by N, followed by K, Ca calcium and phosphorus. Magnesium was present in higher concentrations in chicken litter than in the vermicast. Sulphur was present in the chicken litter, but below QL, as for vermicast. Chicken litter had higher sodium and

manganese contents, and lower aluminium and iron contents than the vermicast. Boron was not detected in either treatment. Cobalt was detected below QL in both treatments.

Table 5-13: Vermicast and chicken litter analyses from each trial and season. C:N results were bulked by season.

Season		**1**			**2**			**3**	
Trial	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
				Vermicast					
C:N		20.9			18.4			19.1	
pH	7.47	7.36	7.30	7.31	7.42	7.33	7.43	7.49	7.36
EC (dS/m)	0.6	1.0	0.9	1.0	1.1	1.2	1.1	0.8	1.1
Ash	78%	78%	78%	78%	77%	78%	78%	78%	77%
Volatile solids	22%	22%	22%	22%	23%	22%	22%	22%	23%
				Chicken litter					
C:N		10.7			11.1			12.6	
pH	8.73	8.87	8.50	8.29	8.48	8.76	9.36	6.96	9.35
EC (dS/m)	13.5	12.9	14.1	15.3	11.7	12.6	12.0	15.3	12.9
Ash	15%	15%	14%	17%	21%	13%	16%	12%	16%
Volatile solids	85%	85%	86%	83%	79%	87%	84%	88%	84%

Both chicken litter and vermicast were tested for heavy metals (Table 5-15). None of the limits for heavy metals were approached or exceeded by the vermicast or chicken litter.

Chicken litter had a higher C% than the vermicast (44.3% vs 15.3%). At 12.5 t FM/ha, the application of vermicast supplied about 917 kg C/ha while at 3 t FM/ha, the application of chicken litter supplied 612 kg C/ha.

5.5.5 Vermicast and chicken litter effects on pH

No difference was detected in baseline soil samples for treatment plots (baseline = prior to application; $p = 0.923$). No significant treatment effects on soil pH were detected at the end of Season 1 ($p = 0.148$) or at the start of Season 2 (0.634). By the end of Season 2, the 12.5 and 25 t FM/ha vermicast treatments had significantly raised pH relative to the Control ($p = 0.007$ and 1.50×10^{-5}, respectively). The 25 t FM/ha vermicast treatment had also increased pH relative to the chicken litter treatment ($p = 1.85 \times 10^{-5}$). By the end of Season 3, the 25 t FM/ha vermicast treatment showed significantly higher pH than the Control ($p = 0.014$) and chicken litter treatment ($p = 0.011$). Soil pHs are reported in Table 5-16.

Table 5-14: Elemental analyses of vermicast and chicken litter over the three seasons. Samples from the same season were bulked before analysis. *Italicised* results are below quantitation limits. ND = not detected. The second half of the table reports estimated nutrient supply. Vermicast is reported at 12.5 t fresh matter (FM)/ha (double the results for 25 t FM/ha). Chicken litter is reported at 3 t FM/ha Note these estimates (and N content in the top half of the table) are based off samples bulked between Trials A-C within seasons.

	Vermicast (mg/kg DM)			**Chicken litter (mg/kg DM)**		
Season	**1**	**2**	**3**	**1**	**2**	**3**
N	7,361	8,330	7,982	41,215	40,238	35,146
P	3,558	3,800	3,781	6,954	5,788	5,720
K	*858*	*718*	*774*	19,592	20,765	21,585
S	*1,572*	*1,332*	*1,319*	*3,652*	*3,825*	*3,749*
Ca	71,740	67,517	65,333	15,910	15,618	14,662
Mg	972	879	892	2,927	3,407	3,013
Al	8,714	8,152	8,492	*33*	*141*	*44*
B	ND	ND	ND	ND	ND	ND
Co	*1.33*	*1.31*	*1.39*	*1.15*	*1.18*	*1.31*
Fe	5,177	5,138	5,289	241	427	362
Na	581	254	436	2,749	2,313	2,863
Mn	231	227	227	377	408	458

Nutrient application	**at 12.5 t FM/ha**			**at 3 t FM/ha**		
	Vermicast (kg nutrient/ha)			**Chicken litter (kg nutrient/ha)**		
Season	**1**	**2**	**3**	**1**	**2**	**3**
N	44.2	52.1	47.9	66.8	57.9	48.5
P	21.3	23.7	22.7	11.3	8.3	7.9
K	*5.2*	*4.5*	*4.6*	31.7	29.9	29.8
S	*9.4*	*8.3*	*7.9*	5.9	5.5	5.2
Ca	430	422	392	25.8	22.5	20.2
Mg	5.8	5.5	5.4	4.7	4.9	4.2
Al	52.3	50.9	51.0	0.1	0.2	0.1
B						
Co	*0.0*	*0.0*	*0.0*	0.0	0.0	0.0
Fe	31.1	32.1	31.7	0.4	0.6	0.5
Na	3.5	1.6	2.6	4.5	3.3	4.0
Mn	1.4	1.4	1.4	0.6	0.6	0.6

Table 5-15: Heavy metal contents detected in vermicast and chicken litter over the three seasons. Samples taken from within the same season were bulked before analysis. These are compared to the limits for land application of biosolids in New Zealand (New Zealand Water and Wastes Association, 2003; Water New Zealand, 2025). Results reported in mg/kg DM. ND = not detected. *Italicised* results are below quantitation limits. The second half of the table reports estimated nutrient supply. Vermicast is reported at 12.5 t fresh matter (FM)/ha (double the results for 25 t FM/ha). Chicken litter is reported at 3 t FM/ha Note these estimates are based off samples bulked between Trials A-C within seasons.

	Vermicast mg/kg DM			**Chicken litter mg/kg DM**			**2003 limit**	**2025 limit**
Season	**1**	**2**	**3**	**1**	**2**	**3**		
As	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	20	30
Cd	*1.03*	*0.90*	*0.94*	*0.24*	*0.22*	*0.27*	3	6.5
Cr	0.40	0.40	0.40	*0.01*	0.03	*0.01*	600	1,500
Cu	0.28	0.30	0.30	1.10	0.77	1.13	300	750
Pb	0.07	0.07	0.07	ND	ND	ND	250	300
Hg			Not tested				2	7.5
Ni	0.04	0.04	0.04	0.04	0.04	0.06	60	135
Zn	0.71	0.72	0.68	0.33	0.33	0.36	600	1,250

Nutrient application						
	Vermicast at 12.5 t FM/ha			**Chicken litter at 3 t FM/ha**		
	1	**2**	**3**	**1**	**2**	**3**
As	0.0	0.0	0.0	0.0	0.0	0.0
Cd	0.6	0.5	0.6	0.0	0.0	0.0
Cr	0.3	0.2	0.3	0.0	0.0	0.0
Cu	0.2	0.2	0.2	0.2	0.1	0.0
Pb	0.0	0.0	0.0	ND	ND	ND
Hg			Not tested			
Ni	0.0	0.0	0.0	0.0	0.0	0.0
Zn	0.4	0.4	0.5	0.0	0.0	0.0

Table 5-16: Soil pH ± standard deviation averaged across plots for the start (before treatment application) and end (at or after crop harvest) of each season. Signifcantly different treatments are indicated by letters a and b.

		Season 1		**Season 2**		**Season 3**	
Trial	**Treatment**	**Start**	**End**	**Start**	**End**	**Start**	**End**
A	Control	6.4 ± 0.1	6.5 ± 0.1	6.4 ± 0.2	6.6 ± 0.1a	6.4 ± 0.2	6.2 ± 0.2a
A	Chicken litter	6.4 ± 0.1	6.6 ± 0.1	6.3 ± 0.1	6.6 ± 0.2a	6.4 ± 0.1	6.2 ± 0.2a
A	12.5 vermicast	6.4 ± 0.1	6.7 ± 0.2	6.5 ± 0.1	6.9 ± 0.1ab	6.4 ± 0.5	6.7 ± 0.1ab
A	25 vermicast	6.4 ± 0.1	6.7 ± 0.3	6.5 ± 0.2	7.0 ± 0.1b	6.7 ± 0.1	6.7 ± 0.3b
B	Control	6.8 ± 0.2	6.9 ± 0.2	6.7 ± 0.1	6.8 ± 0.2a	6.9 ± 0.2	6.7 ± 0.2a
B	Chicken litter	6.8 ± 0.2	6.8 ± 0.2	6.6 ± 0.2	6.9 ± 0.2a	6.9 ± 0.2	6.7 ± 0.2a
B	12.5 vermicast	6.8 ± 0.2	7.0 ± 0.2	6.7 ± 0.2	7.0 ± 0.2ab	7.0 ± 0.2	7.0 ± 0.2ab
B	25 vermicast	6.8 ± 0.1	7.1 ± 0.1	6.7 ± 0.2	7.2 ± 0.1b	7.2 ± 0.2	7.2 ± 0.1b
C	Control	6.7 ± 0.1	6.8 ± 0	6.9 ± 0.1	6.7 ± 0.1a	6.6 ± 0.0	7.0 ± 0.1a
C	Chicken litter	6.7 ± 0.2	6.9 ± 0.2	6.9 ± 0.1	6.8 ± 0.1a	6.7 ± 0.2	7.0 ± 0.2a
C	12.5 vermicast	6.6 ± 0.2	6.9 ± 0.1	6.9 ± 0.1	6.9 ± 0.2ab	6.7 ± 0.2	7.2 ± 0.2ab
C	25 vermicast	6.6 ± 0.2	7.0 ± 0.2	6.9 ± 0.1	7.0 ± 0.2b	6.8 ± 0.1	7.4 ± 0.1b

5.5.6 Onions

Each of the three seasons of onion data were analysed individually before a multi season analysis was conducted. Table 5-17 and Table 5-18 summarise data across the three individual seasons and are referred to under each of the three subsections. Figure 5-8 and Figure 5-10 display seasonal trends in yield and density. Appendix 3: additional statistical test results includes further data.

Table 5-17: Average statistics for onion crops grown each season in Trials A, B and C, including analysis of variance (ANOVA) and Levene's test p values. Average yield and count data are from the bulk dataset. Average onion masses are from the individual dataset. All reported averages are ± standard deviation. Statistical significance is indicated by * and a, b, c groupings. Results from post hoc (actual power) and a priori power analyses (minimum replicates to achieve power of at least 0.80) at $\alpha = 0.05$ are also reported for total sample sizes of 16 and n = 4.

Treatment	**Average density (onions/m^2)**	**Average onion mass (g/onion)**	**Average yield (kg/m^2)**
Season 1, Trial A			
Control	105.1 ± 2.4	105.2 ± 8.6	11.6 ± 0.8
Chicken litter	107.2 ± 4.5	103.6 ± 11.1	11.4 ± 1.0
12.5 t/ha vermicast	106.0 ± 5.1	103.5 ± 9.5	11.3 ± 0.5
25 t/ha vermicast	107.1 ± 2.7	102.9 ± 6.3	11.5 ± 0.5
ANOVA p-values	*0.217*	*0.893*	*0.397*
Levene's test p-values	*0.791*	*0.896*	*0.901*
Cohen's F	*0.116*	*0.109*	*0.206*
Power at α = 0.05	*0.060*	*0.058*	*0.081*
Type II error rate	*94%*	*94%*	*92%*
Minimum replicates required	*204*	*231*	*66*
Season 2, Trial C			
Control	83.4 ± 3.2 a	174.5 ± 8.9	14.6 ± 1.2
Chicken litter	70.9 ± 4.5 b	191.0 ± 15.8	13.9 ± 0.9
12.5 t/ha vermicast	77.1 ± 7.0 ab	175.6 ± 13.4	14.0 ± 0.8
25 t/ha vermicast	77.5 ± 2.9 ab	184.5 ± 17.6	14.1 ± 1.3
ANOVA p-values	*0.018**	*0.183*	*0.0.301*
Levene's test p-values	*0.495*	*0.697*	*0.975*
Cohen's F	*0.540*	*0.547*	*0.285*
Power at α = 0.05	*0.309*	*0.316*	*0.112*
Type II error rate	*69%*	*68%*	*89%*
Minimum replicates required	*11*	*11*	*35*
Season 3, Trial B			
Control	75.4 ± 3.9 b	112.3 ± 9.6 b	8.5 ± 0.3 bc
Chicken litter	53.4 ± 5.5 c	144.2 ± 18.6 a	7.8 ± 0.8 c
12.5 t/ha vermicast	83.9 ± 6.5 ab	102.0 ± 7.7 b	9.2 ± 0.4 ab
25 t/ha vermicast	88.0 ± 2.1 a	110.6 ± 6.2 b	10.1 ± 0.9 a
ANOVA p-values	*1.19×10^{-6}**	*6.00×10^{-4}**	*0.003**
Levene's test p-values	*0.240*	*0.592*	*0.334*

Table 5-18: Size distribution of onions by treatment including the number of onions per size class and average proportion of onions per size class. Data are from the individual dataset. Proportions are ± SD. Statistical significance is indicated by *. Where Levene's test is non-significant, significant analyses of variance (ANOVA) results are indicated by a, b, c groupings.

Treatment	**Pickling (<40 mm diameter)**		**Small (40-60 mm diameter)**		**Medium (60-80 mm diameter)**		**Large (>80 mm diameter)**	
	Average count (onions/treatment)	**Proportion of total onions (%)**	**Average count (onions/treatment)**	**Proportion of total onions (%)**	**Average count (onions/treatment)**	**Proportion of total onions (%)**	**Average count (onions/treatment)**	**Proportion of total onions (%)**
Season 1, Trial A								
Control	17.2 ± 4.6	5.3 ± 1.5	171.2 ± 38.4	52.5 ± 10.2	131.2 ± 25.0	40.7 ± 9.3	4.5 ± 2.6	1.4 ± 0.9
Chicken litter	15.5 ± 5.3	4.8 ± 1.6	174.2 ± 32.1	53.5 ± 7.8	132.0 ± 26.1	40.9 ± 9.0	2.8 ± 0.5	0.9 ± 0.2
12.5 t/ha vermicast	14.5 ± 4.1	4.5 ± 1.0	179.0 ± 38.5	55.1 ± 9.1	127.0 ± 16.7	40.0 ± 8.9	1.7 ± 0.6	0.4 ± 0.3
25 t/ha vermicast	16.2 ± 3.5	5.1 ± 1.1	177.0 ± 26.3	55.4 ± 6.4	123.5 ± 23.4	38.8 ± 7.4	2.2 ± 0.5	0.7 ± 0.2
ANOVA p-values	*0.758*	*0.701*	*0.945*	*0.756*	*0.635*	*0.885*	*0.062*	*0.608*
Levene's test p-values	*0.959*	*0.963*	*0.956*	*0.886*	*0.668*	*0.990*	*0.035**	*0.028**
Season 2, Trial C								
Control	8.2 ± 3.6	3.5 ± 1.6	47.8 ± 7.4	19.9 ± 3.3	152.0 ± 13.4	63.1 ± 2.3	32.8 ± 7.7	13.6 ± 2.8
Chicken litter	6.0 ± 3.6	2.8 ± 1.1	36.0 ± 12.4	17.5 ± 3.8	121.0 ± 28.0	59.1 ± 3.6	41.0 ± 6.9	20.6 ± 5.4
12.5 t/ha vermicast	7.2 ± 2.9	3.2 ± 1.1	48.0 ± 6.1	21.6 ± 1.0	131.5 ± 27.2	58.6 ± 6.4	35.8 ± 11.4	16.6 ± 7.5
25 t/ha vermicast	6.0 ± 3.7	2.7 ± 1.5	39.2 ± 14.0	17.9 ± 5.8	133.2 ± 15.6	61.4 ± 4.9	38.5 ± 11.2	18.0 ± 6.3
ANOVA p-values	*0.778*	*0.867*	*0.254*	*0.328*	*0.101*	*0.353*	*0.509*	*0.144*
Levene's test p-values	*0.968*	*0.884*	*0.464*	*0.229*	*0.533*	*0.714*	*0.674*	*0.672*
Season 3, Trial B								
Control	29.5 ± 6.6 a	13.2 ± 2.0 a	91.5 ± 20.9 ab	41.0 ± 5.3 ab	95.2 ± 16.0 b	43.2 ± 5.8 ab	5.5 ± 2.4 b	2.6 ± 1.6 b
Chicken litter	13.5 ± 5.5 b	8.2 ± 3.5 b	50.0 ± 20.1 b	29.1 ± 6.3 b	88.0 ± 10.1 b	53.2 ± 3.4 a	15.2 ± 6.1 a	9.4 ± 4.45 a
12.5 t/ha vermicast	39.2 ± 11.5 a	15.0 ± 3.6 a	118.8 ± 17.9 a	46.0 ± 4.2 a	96.2 ± 4.6 b	37.6 ± 3.3 b	3.2 ± 1.7 b	1.3 ± 0.79 b
25 t/ha vermicast	35.2 ± 5.4 a	12.7 ± 1.4 ab	117.2 ± 9.8 a	42.3 ± 3.4 ab	118.8 ± 6.9 a	42.8 ± 1.7 ab	8.7 ± 1.5 ab	2.3 ± 1.6 b
ANOVA p-values	*3.86×10^{-4}**	*0.007**	*0.005**	*0.028**	*0.005**	*0.016**	*0.011**	*0.006**
Levene's test p-values	*0.943*	*0.361*	*0.757*	*0.788*	*0.688*	*0.160*	*0.489*	*0.589*

5.5.6.1 Onions, Season 1, Trial A

No significant differences were detected between treatments in the first season for yield ($p = 0.915$), density ($p = 0.858$) or individual onion mass ($p = 0.986$). The lowest yield was 11.3 ± 0.5 kg/m^2 for the 12.5 t/ha vermicast treatment and the highest was 11.6 ± 0.8 kg/m^2 for the Control. The lowest density was 105.1 ± 2.4 onions/m^2 for the Control and the highest was 107.2 ± 4.5 onions/m^2 for the chicken litter treatment. The lowest average onion mass was 102.9 ± 6.3 g/onion for the 25 t/ha vermicast treatment. The highest was 105.2 ± 8.6 g/onion for the Control. Data are from Table 5-17 and are displayed in Figure 5-8, Figure 5-9 and Figure 5-10.

Regardless of treatment, most onions fitted into the small onion category. The size distribution of onions between size classes was similar between treatments. About 5% of onions were classes as pickling, 54% as small, 40% as medium and 1% as large. There were no treatment differences in onion size. Levene's test indicated heterogeneity in the count of large onions ($p = 0.035$) and therefore violation of the homogeneity assumption. However, given the small sample size ($n = 4$ per treatment), few total large onions, and no signs of heteroscedasticity in residual plots this was not concerning. Data are from Table 5-18.

According to Q-Q plots (not displayed) and Shapiro-Wilk tests (Table 8-11), all data were normally distributed.

A significant column effect was detected in yield ($p = 0.001$), individual onion masses ($p = 0.007$) and onion counts ($p = 0.001$). Column A grew the lowest yield and the lightest onions, followed by Columns D, C and B respectively. Column B grew the fewest total onions, followed by Columns C, A and D respectively.

A row effect was detected in the proportion of medium onions ($p = 0.036$) and both a column and row effect were detected for large onions ($p = 0.009$ and 0.036, respectively).

A Pearson's product-moment correlation ($r = -0.623$, $p = 0.010$) confirmed the presence of a density effect across all plots, where higher onion densities are correlated with lower average onion masses. This was seen in the Control treatment which had the highest average onion mass and lowest density of onions. The 95% confidence intervals for this relationship were -0.85 to -0.18. The r^2 value was 0.39, indicating that 39% of the variation in onion mass was explained by onion density.

5.5.6.2 Onions, Season 2, Trial C

No significant differences were detected in yield for Season 2. The lowest yield was 13.9 ± 0.9 kg/m^2 for the chicken litter treatment while the highest was 14.6 ± 1.2 kg/m^2 for the Control. A significant difference was detected in onion density between the Control (83.4 ± 3.2 onions/m^2) and the chicken litter treatment (70.9 ± 4.5 onions/m^2), but not the vermicast treatments. The lowest average onion mass was 174.5 ± 8.9 g/onion for the Control. The highest was 191.0 ± 15.8 g/onion for the chicken litter treatment, but these differences were not significant. Data are from Table 5-17 and are displayed in Figure 5-8, Figure 5-9 and Figure 5-10.

Most onions fitted into the medium category. The size distribution of onions between size classes was similar between treatments, though there appeared to be more variation in large onions between treatments. About 3% of onions were classed as pickling, 20% as small, 60% as medium and 17% as large (Table 5-18).

According to Q-Q plots (not displayed) and Shapiro-Wilk tests (Table 8-11), all data were normally distributed, except for the chicken litter treatment. Normality tests at the subplot (per m^2) level indicated that the chicken litter treatment was not normally distributed. Shapiro-Wilk test p-values were 0.027 and 0.046 for mass and count of onions in the bulk dataset for the chicken litter treatment. From the Q-Q plots and 1.5 interquartile range, two subplot outliers were identified in plots B1 and D2 (averages from each plot/experimental unit were calculated from eleven subplots). Investigation of the raw data confirmed that these two subplots had genuinely low numbers of onions leading to low yields and densities. The chicken litter treatment showed more variable responses than other treatments in this season. While the subplot data were non-normally distributed, this was due to genuine biological variation and a small dataset. Note that subplots were not the experimental units for the analysis – the treatment averages were. When subplots were averaged to form plot-level experimental units for the statistical analysis, the variation in the data was no longer significant and the data were considered normal and suitable for ANOVA.

Significant column effects were detected in onion density ($p = 0.043$) and yield ($p = 0.006$). Column B grew the fewest onions, followed by Columns D, A and C respectively. Column A had the lowest yield, followed by B, D and C. Initially, a row effect was detected for yield ($p = 0.046$), but this was not significant after Bonferroni adjustment.

A Pearson's product-moment correlation ($r = -0.712$, $p = 0.002$) confirmed the presence of a density effect across all plots, where higher onion densities are correlated

with lower average onion masses. This is seen in the Control treatment (highest density, lowest average onion mass) and the reciprocal in the chicken litter treatment (lowest density, highest mass). The 95% confidence intervals for this relationship were -0.89 to -0.33. The r^2 value was 0.51, indicating that 51% of the variation in onion mass was explained by onion density.

5.5.6.3 Onions, Season 3, Trial B

In the final season, significant differences were detected in all parameters measured: yield, density and onion mass, as well as the count and proportion of onions in each size class (Table 5-17 and Table 5-18). The highest yield was produced by the 25 t/ha vermicast treatment (10.1 ± 0.9 kg/m^2), intermediate by the 12.5 t/ha vermicast treatment (9.2 ± 0.4 kg/m^2), Control (8.5 ± 0.3 kg/m^2) and the lowest by the chicken litter treatment (7.8 ± 0.8 kg/m^2). The difference between the 25 t/ha vermicast compared to the Control and chicken litter treatments was significant ($p = 0.003$). The difference between the 12.5 t FM/ha vermicast and chicken litter treatments was also significant. Similarly, the highest densities were produced by the 12.5 and 25 t/ha vermicast treatments (83.9 ± 6.5 and 88.0 ± 2.1 onions/m^2) and the lowest by the chicken litter treatment (53.4 ± 5.5 onions/m^2). The Control had a density between these treatments of 75.4 ± 3.9 onions/m^2. The differences between the two vermicast treatments compared to the Control and chicken litter treatments were highly significant ($p = 1.19 \times 10^{-4}$). The lowest average onion mass was 102.0 ± 7.7 g/onion for the 12.5 t/ha vermicast treatment while the highest was 144.2 ± 18.6 g/onion for the chicken litter treatment ($p = 6.00 \times 10^{-4}$). The 25 t/ha vermicast and Control treatments were not significantly different from the 12.5 t/ha vermicast treatment for average onion mass. Data are from Table 5-17 and are displayed in Figure 5-8, Figure 5-9 and Figure 5-10.

Most onions fit into the small and medium categories. The size distribution of onions between size classes varied between treatments, with chicken litter producing bigger onions on average (8% pickling, 29% small, 53% medium and 9% large). These differences were significant (refer Table 5-18). The Control, and two vermicast treatments tended to produce small and medium onions with similar distributions of about 14% of onions classed as pickling, 43% as small, 41% as medium and 2% as large (Table 5-18). A similar trend in distribution of the number of onions per treatment was observed where the chicken litter and Control/vermicast treatments were significantly different, except for the count of medium onions per treatment, where chicken litter, Control and the 12.5 t/ha vermicast treatment produced fewer medium onions than the 25 t/ha

vermicast treatment. The p-values for the size distribution results are reported in Table 5-18.

According to Q-Q plots (not displayed) all data were normally distributed. Shapiro-Wilk tests (Table 8-11), indicated all data were normally distributed, except for the proportion of large onions ($p = 0.002$). Given the small total number of large onions (0-16% of total onions per plot, regardless of treatment) and the small sample size (4 replicates per treatment), this measurement may be considered unreliable.

A column effect was detected for individual onion mass ($p = 0.023$). Column C grew the lightest onions, followed by D, B and A. A column effect was detected for the count and proportion of pickling onions ($p = 0.005$ and 0.015, respectively). Column B produced the highest proportion and count of pickling onions, followed by C, D and A.

A Pearson's product-moment correlation ($r = -0.816$, $p = 0.0001$) confirmed the presence of a density effect across all plots, that when onion density is higher, average onion mass is lower. This is seen in the vermicast treatments (highest densities, lowest masses) and the reciprocal in the chicken litter treatment (lowest density, highest mass). The 95% confidence intervals for this relationship were -0.93 to -0.54. The r^2 value was 0.51, indicating that 51% of the variation in onion mass was explained by onion density.

Fusarium oxysporum (basal rot) was detected in Season 3, this was treated as a measure of onion quality. Average ± standard deviation for each treatment was 2.9 ± 2.1% (Control), 3.5 ± 2.6% (chicken litter) 2.1 ± 1.0% (12.5 t FM/ha vermicast) and 4.0 ± 1.9% (25 t FM/ha vermicast). The presence/absence of it on individual bulbs was recorded and an ANOVA was performed. The p value for the test was 0.608, so there was no significant difference between treatments. A post-hoc power analysis (Cohen's $F = 0.398$) indicated a large treatment effect with low power (0.181) and an 82% chance of a Type II error (false negative). A priori analysis reported that 29 replicates would have been required to detect an effect. In this analysis, the difference in the number of onions per treatment was considered to be a factor in this (more onions in the 25 t FM/ha treatment could explain the higher incidence of *F. oxysporum* in this treatment, however a Pearson's product-moment correlation showed that this was not the case ($p = 0.930$).

5.5.6.4 Power analyses

Post hoc and a priori power analyses were performed to determine the likelihood of a statistically significant difference being overlooked and the minimum number of replicates that would have been required to detect a statistically significant difference. In Season 1, onion mass and count were very underpowered (94% chance of a Type II error).

However, Cohen's F values for both parameters were 0.11 – close to the threshold of 0.10 for a small effect. While the trial was underpowered, there was a genuinely small difference between treatments. A medium effect was detected for yield, and comparatively fewer minimum replicates (66 vs >200) were calculated, though this is still many more than were possible at the trial scale. As the timing of the application of vermicast and chicken litter may have limited the effect sizes, the low power found for this trial would not have been strong enough evidence to modify the trial design.

For Season 2, the trials were underpowered for onion mass and count, though a large effect size was detected (Cohen's F was >0.40 for both parameters). There was a lower likelihood of not detecting a genuine significant difference than Season 1, however this trial was also underpowered. Far fewer minimum replicates were recommended (11 for density and mass and 35 for yield) for Season 2, indicating a substantially larger treatment effect size in that season, suggesting that treatment applications affected onion production more in Season 2, despite the effects remaining statistically non-significant.

Power analysis was not required for Season 3 as significant differences were detected, though exploratory testing indicated a large effect size was detected.

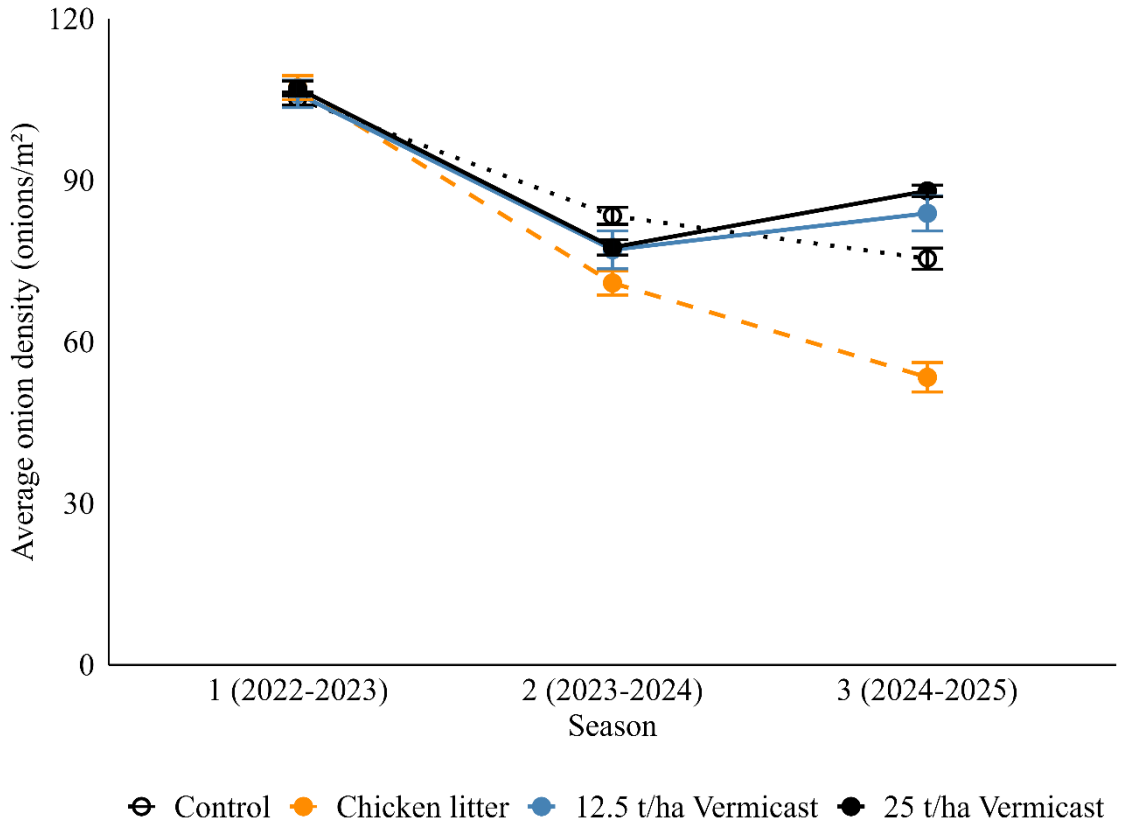


Figure 5-8: Seasonal onion densities per treatment over the three-year trial. Error bars are ± standard deviation. The trial moved location each season. See text for details.

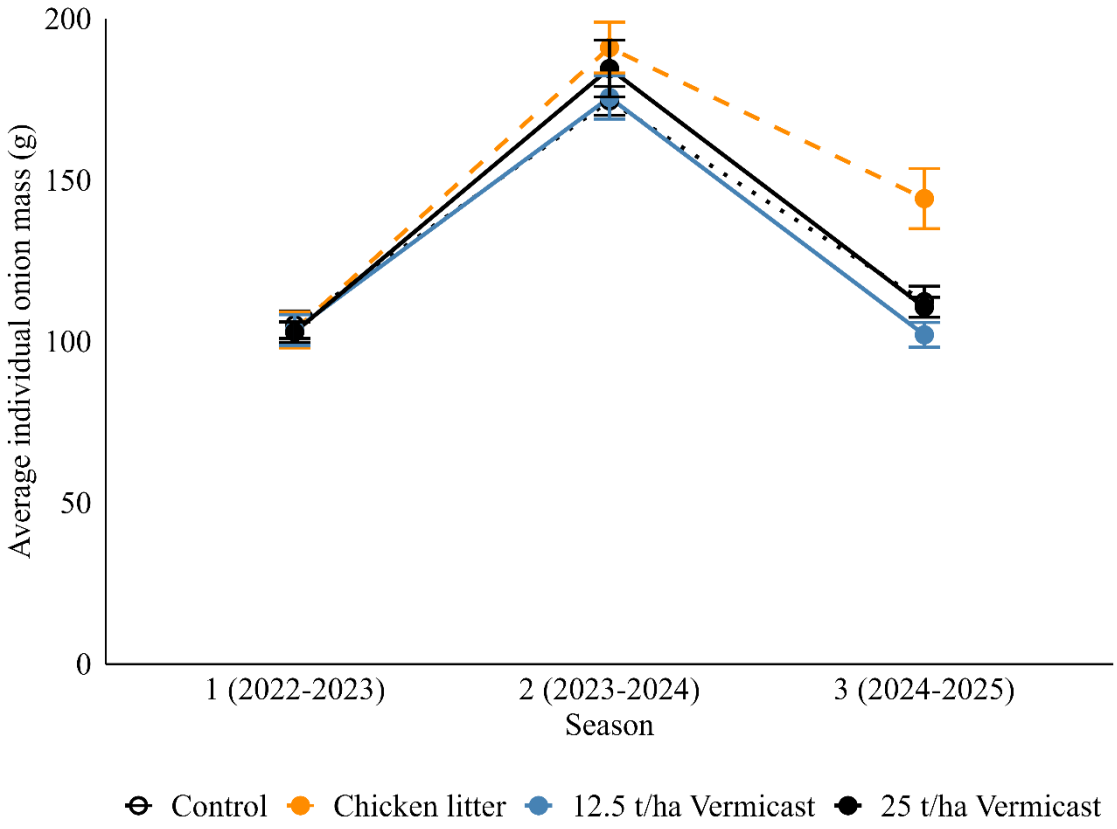


Figure 5-9: Seasonal average onion mass per treatment over the three-year trial. Error bars are ± standard deviation. The trial moved location each season. See text for details.

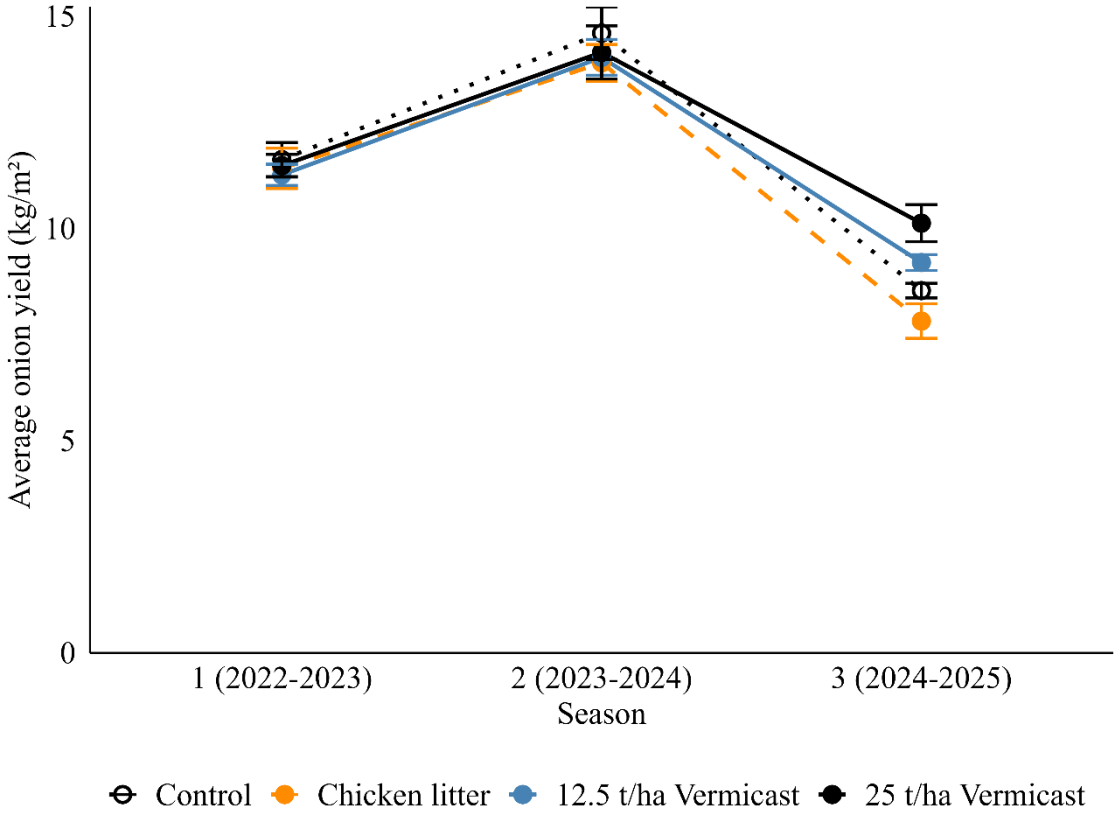


Figure 5-10:Seasonal onion yields per treatment over the three-year trial. Error bars are ± standard deviation. The trial moved location each season. See text for details.

5.5.6.5 Onions, multi-season analysis

Season had a significant effect on yield and density ($p = 1.9 \times 10^{-11}$ and 8.4×10^{-11}, respectively). For Seasons 1, 2, and 3, seasonal yield averaged across all treatments was 11.4, 14.2 and 8.9 kg/m^2 respectively. Average seasonal density in Season 1 (106.4 onions/m^2) differed from densities in Seasons 2 and 3 (77.2 and 75.2 onions/m^2). A significant interaction was detected between treatment and season ($p = 1.5 \times 10^{-8}$) in onion density. Levene's test failed ($p = 0.0006$), indicating variances were not equal across seasons, however, ANOVA was considered robust given the balanced design ($n = 16$ plots per season) and the large effect size of the interaction. In addition, Welch's one-way ANOVA (assuming unequal variances) confirmed the significance of treatment-season effects ($F = 51.3$, $p = 1.0 \times 10^{-9}$) supporting the robustness of the interaction finding. The interaction meant that the size of the effect of treatment on yield and density depended on the season.

Onions grown in Season 2 tended to be larger and heavier than onions grown in Season 1, and Season 3 (Figure 5-9), though seasonal average onion masses were statistically significant to each other ($p = 0.026$).

According to Q-Q plots and Shapiro-Wilk tests, all data were normally distributed, except for the chicken litter treatment in Season 2 with Shapiro-Wilk test values of $p = 0.027$ and 0.046 for mass and density of onions in the bulk dataset, respectively. As stated in the Season 2 results section, two subplot outliers were identified from plots B1 and D2 as having low densities of onions leading to low onion count and low bulk mass. When subplots were averaged to form plot-level experimental units for the statistical analysis, the variation in the data was no longer significant and the data were considered normal and suitable for ANOVA. Density in Season 3 was similar to Season 2, though it was low in the chicken litter treatment. This had an effect on onion mass in the chicken litter treatment (lowest density, but highest onion mass). However, this did not translate to greater yields. Overall, yield was depressed in Season 3.

5.5.6.6 Financial benefit of vermicast application

The financial benefit of a 9.1 t/ha increase in onion yield from vermicast applied at 25 t FM/ha was calculated to be $812/ha. This was at the base prices of $29.95/t for vermicast, $23.00/t for transport, $6.00/t for spreading, and a farmgate profit of $250.00/t onions produced. The results are presented in Table 5-19.

The financial benefit of the 25 t FM/ha vermicast application remained positive throughout the sensitivity analysis where costs were increased by 20 and 50%, profit was reduced by 20 and the worst-case scenarios where costs were increased by up to 50% and profit was decreased by 20%. Farmgate profit had the most impact on total profit for the yield increase. Total additional income for a hypothetical 50 ha crop was $40,598 total at the base values.

Table 5-19: Cost-benefit and sensitivity analyses for application of vermicast at 25 t FM/ha to onions. Analysis based on significant yield data from Season 3. Costs and benefits are from retail/industry sources. Reported values rounded to the nearest $.

Variable	Base	Cost sensitivity		Profit sensitivity		Worst case	
		20% increase	50% increase	20% decrease	50% decrease	± 20%	± 50%
Vermicast costs							
Vermicast $/t vermicast	30	36	$43	30	30	36	43
Transport $/t vermicast	23	28	33	23	23	28	33
Spreading $/t vermicast	6	7	9	6	6	7	9
Total cost $/ha	1,474	1,769	2,122	1,474	1,474	1,769	2,122
Profit $/t onions	250	250	250	200	125	200	125
Benefit of vermicast $/ha	2,286	2,286	2,286	1,829	1,143	1,829	1,143
Increased yield value $/ha	812	517	164	355	331	60	979
Total profit for 50 ha crop	40,598	25,861	8,176	17,741	16,545	3,004	48,967

The following results are reported in Table 8-16 (Appendix 3: additional statistical test results). A yield sensitivity analysis showed that at the base values, applying 25 t FM/ha vermicast would have to increase yield by 6.7 t onions/ha to produce a benefit of $200/ha. A financial sensitivity analysis was performed on the reduced yield values and showed that the net benefit was highly sensitive to costs increasing by ≥20% or profit reducing by ≥20%, making the application of vermicast in such cases financially unviable.

5.5.7 Potatoes

5.5.7.1 Yield analysis

The potato variety grown in Seasons 1 and 2 were Crop 78. In Season 3, a different variety called ‘Moonlight’ was sown in the trial area. Both Crop 78 and Moonlight are French fry variety potatoes. Due to the difference in variety, a multi season analysis was not possible for potatoes. In this section, seasons are reported independently, though raw data and figures will display all three seasons together. Raw data for all seasons are reported in Table 5-21 and Table 5-22. Average density, average individual tuber mass

and average yield are displayed in Figure 5-11 to Figure 5-13. Shapiro-Wilk p-values can be found in Table 8-12 (Appendix 3: additional statistical test results)

In Season 1, there were no treatment effects on yield, tuber counts or tuber sizes. However, the mass of potatoes in the medium size class initially differed significantly between treatments ($p = 0.019$) and across columns ($p = 0.043$), though no significant differences between individual treatment pairs were identified following Bonferroni correction of Fisher's LSD. Post hoc power analyses showed that even at $n = 3$, the effect size was large (Cohen's $F = 0.972$ and 0.707 for density and yield). Power for yield and density were low at ($p = 0.589$ and 0.339, respectively), indicating a 41 and 66% chance, respectively, of Type II errors (false negative). A priori power analysis showed that a minimum of five replicates would have been required to detect a significant difference in density and seven would have been required for yield. Power analyses were not conducted on average tuber mass as this was calculated from density and yield.

In Season 2, there were no significant treatment differences in yield, tuber density or average tuber mass. The count and mass of undersized tubers differed significantly across rows ($p = 0.004$ and 0.018, respectively), indicating a spatial gradient in undersized tuber production across the field. Levene's test indicated heterogeneity of variance for yield ($p = 0.025$) and undersized tuber mass ($p = 0.040$), violating the ANOVA assumption of homogeneity of variances. As no significant treatment effects were detected, these violations do not affect the interpretation of results. Post hoc power analysis showed very low power for density (0.097) and low power for yield (0.390). The effect size for density was small ($F = 0.249$) and a priori power analysis indicated that a minimum of 45 replicates would have been required to detect a significant difference. The yield effect size was larger ($F = 0.613$) and fewer minimum replicates (nine) were calculated. Row effects were detected for undersized potatoes. Row 1 produced the most undersized potatoes ($p = 0.018$), while Row 2 produced the greatest mass of undersized potatoes ($p = 0.004$).

In Season 3, there were no significant treatment differences in yield, tuber density or average tuber mass. A significant difference was detected between the 12.5 t FM/ha treatment and the Control ($p = 0.018$; Table 5-23). The 12/5 t FM/ha vermicast treatment produced 107.7 ± 3.8 tubers/total plot sample area while the Control produced 85.0 ± 9.5 tubers/total plot sample area. A significant Column effect was detected ($p = 0.023$) for the count of large potatoes. Column B had significantly fewer large potatoes than Column A, indicating spatial variation, but this was accounted for in the trial design. Post hoc power analyses indicated low power in Season 3 for density and yield (0.158 and 0.654,

respectively). A priori analysis indicated a minimum of 15 and four replicates would have been required to detect a significant effect in the respective parameters.

5.5.7.2 Quality analysis

The Shapiro-Wilk test for normality was borderline ($p = 0.046$) for potato chip whiteness of the chicken litter treatment. These results can be found in Table 8-13. Inspection of the residual diagnostic plots showed no systematic departures from normality or homogeneity of variance, and ANOVA was considered appropriate.

No significant differences were detected in the quality analyses of the Moonlight potatoes from Season 3. A column effect was detected for specific gravity indicating spatial variation where Column B had lower average specific gravity than Columns A and C, but this was accounted for in the trial design.

Table 5-20: Specific gravity of fresh and whiteness of fried potatoes in Season 3. SD = standard deviation.

Treatment	**Specific gravity**	**SD**	**Whiteness (%)**	**SD**
Control	1.07	2.4×10^{-3}	72.4	4.29
Chicken litter	1.07	5.5×10^{-3}	74.6	1.1
12.5 t/ha vermicast	1.08	3.1×10^{-3}	70.6	3.28
25 t/ha vermicast	1.07	3.4×10^{-3}	74.7	1.47
ANOVA p-values	*0.184*		*0.186*	
Levene's test p-values	*0.411*		*0.177*	
Cohen's F	*0.404*		*0.688*	
Power at α = 0.05	*0.186*		*0.480*	
Type II error rate	*81%*		*52%*	
Minimum replicates required	*18*		*7*	

An observation made while sampling Season 2 potatoes was the presence of a lumpy texture on some potatoes – possibly caused by root knot nematode. The symptoms/causal agent were not diagnosed. This observation was not made in any other season/trial.

Table 5-21: Average statistics for potato crops grown each season in Trials A, B and C, including analysis of variance (ANOVA) and Levene's test p values. All reported averages are ± standard deviation. Results from post hoc (actual power) and a priori power analyses (minimum replicates to achieve power of at least 0.80) at $\alpha = 0.05$ are also reported for total sample sizes of 12 and n = 4, except for Season 2 which had 16 and 4 respectively. Note that variety varied by season: Seasons 1 and 2 were Crop 78, Season 3 was Moonlight.

Treatment	**Average density (potatoes/m^2)**	**Average potato mass (g/tuber)**	**Average yield (kg/m^2)**
Season 1, Trial B			
Control	45.3 ± 8.4	118.7 ± 17.0	5.3 ± 0.7
Chicken litter	48.1 ± 8.0	107.2 ± 49.2	4.9 ± 1.6
12.5 t/ha vermicast	35.5 ± 1.9	121.5 ± 8.5	4.3 ± 0.5
25 t/ha vermicast	42.9 ± 0.4	135.8 ± 11.3	5.8 ± 0.5
ANOVA p-values	*0.231*	*0.690*	*0.297*
Levene's test p-values	*0.203*	*0.285*	*0.654*
Cohen's F	*0.972*		*0.707*
Power at α = 0.05	*0.589*		*0.339*
Type II error rate	*41%*		*66%*
Minimum replicates required	*5*		*7*
Season 2, Trial A			
Control	51.9 ± 10.7	167.6 ± 48.9	8.3 ± 1.0
Chicken litter	53.5 ± 5.6	153.4 ± 17.7	8.1 ± 0.1
12.5 t/ha vermicast	50.6 ± 11.0	150.7 ± 29.7	7.4 ± 0.6
25 t/ha vermicast	47.6 ± 11.8	153 ± 18.6	7.2 ± 1.4
ANOVA p-values	*0.723*	*0.716*	*0.407*
Levene's test p-values	*0.371*	*0.439*	*0.025**
Cohen's F	*0.249*		*0.613*
Power at α = 0.05	*0.097*		*0.390*
Type II error rate	*90%*		*41%*
Minimum replicates required	*45*		*9*
Season 3, Trial C			
Control	64.4 ± 1.4	130.4 ± 17.8	8.4 ± 1.0
Chicken litter	64.0 ± 10.8	143.7 ± 9.0	9.2 ± 1.2
12.5 t/ha vermicast	70.4 ± 8.5	154.2 ± 18.9	10.8 ± 1.1
25 t/ha vermicast	65.5 ± 0.8	139.7 ± 10.6	9.2 ± 0.8
ANOVA p-values	*0.615*	*0.380*	*0.132*
Levene's test p-values	*0.256*	*0.940*	*0.979*
Cohen's F	*0.452*		*1.042*
Power at α = 0.05	*0.158*		*0.654*
Type II error rate	*84%*		*35%*
Minimum replicates required	*15*		*4*

Table 5-22: Size distribution of onions by treatment including the number of onions per size class and average proportion of onions per size class. Data are from the individual dataset. Proportions are ± SD. Statistical significance is indicated by *. Note that variety varied by season: Seasons 1 and 2 were Crop 78, Season 3 was Moonlight.

Treatment	Undersized (<40 mm diameter)		Small (40-50 mm diameter)		Medium (50-60 mm diameter)		Large (>60 mm diameter)	
	Average mass (kg potatoes/ treatment)	Proportion of total tubers (%)	Average mass (kg potatoes/ treatment)	Proportion of total tubers (%)	Average mass (kg potatoes/ treatment)	Proportion of total tubers (%)	Average mass (kg potatoes/ treatment)	Proportion of total tubers (%)
Season 1, Trial B								
Control	0.147 ± 0.10	2.7 ± 1.7	0.586 ± 0.08	11.2 ± 2.3	2.23 ± 0.35	42.0 ± 4.3	2.348 ± 0.53	44.1 ± 7.8
Chicken litter	0.307 ± 0.37	9.1 ± 12.8	0.489 ± 0.13	11.2 ± 5.8	1.511 ± 0.45	31.2 ± 3.1	2.591 ± 1.64	48.5 ± 20.2
12.5 t/ha vermicast	0.134 ± 0.04	3.2 ± 1.3	0.474 ± 0.17	11.4 ± 5.1	1.586 ± 0.47	36.2 ± 8.0	2.131 ± 0.47	49.2 ± 7.9
25 t/ha vermicast	0.099 ± 0.02	1.7 ± 0.5	0.453 ± 0.10	7.7 ± 1.3	2.392 ± 0.37	40.9 ± 3.9	2.887 ± 0.35	49.6 ± 5.2
ANOVA p-values	*0.642*	*0.570*	*0.700*	*0.701*	*0.019**	*0.098*	*0.812*	*0.953*
Levene's test p-values	*0.365*	*0.414*	*0.939*	*0.540*	*0.998*	*0.712*	*0.364*	*0.479*
Season 2, Trial A								
Control	0.33 ± 0.18	4.1 ± 2.6	0.539 ± 0.27	6.7 ± 3.9	1.509 ± 0.39	18.1 ± 3.5	5.945 ± 1.13	71.1 ± 8.4
Chicken litter	0.288 ± 0.09	3.5 ± 1.1	0.605 ± 0.28	7.5 ± 3.5	1.405 ± 0.39	17.3 ± 4.8	5.844 ± 0.67	71.8 ± 7.8
12.5 t/ha vermicast	0.359 ± 0.16	4.8 ± 2.0	0.594 ± 0.28	8.0 ± 3.7	1.308 ± 0.36	17.5 ± 3.8	5.132 ± 0.53	69.7 ± 8.2
25 t/ha vermicast	0.257 ± 0.09	3.6 ± 0.9	0.602 ± 0.24	8.3 ± 2.5	1.47 ± 0.62	20.1 ± 6.1	4.852 ± 0.85	68.0 ± 7.4
ANOVA p-values	*0.400*	*0.6244*	*0.759*	*0.0.458*	*0.927*	*0.799*	*0.449*	*0.769*
Levene's test p-values	*0.040**	*0.038**	*0.965*	*0.959*	*0.752*	*0.740*	*0.884*	*0.947*
Season 3, Trial C								
Control	0.138 ± 0.02	1.7 ± 0.4	0.355 ± 0.09	4.4 ± 1.6	1.448 ± 0.41	17.8 ± 7.4	6.506 ± 1.36	77.1 ± 7.7
Chicken litter	0.106 ± 0.02	1.1 ± 0.1	0.261 ± 0.07	2.8 ± 0.4	1.333 ± 0.16	14.6 ± 1.5	7.453 ± 1.02	81.4 ± 1.8
12.5 t/ha vermicast	0.263 ± 0.22	2.3 ± 1.7	0.365 ± 0.25	3.3 ± 2.0	1.408 ± 0.49	13.0 ± 4.4	8.74 ± 0.67	81.4 ± 6.8
25 t/ha vermicast	0.141 ± 0.06	1.6 ± 0.8	0.359 ± 0.06	4.0 ± 0.9	1.570 ± 0.19	17.3 ± 3.2	7.083 ± 0.95	77.2 ± 4.5
ANOVA p-values	*0.404*	*0.470*	*0.727*	*0.334*	*0.742*	*0.393*	*0.089*	*0.373*
Levene's test p-values	*0.281*	*0.352*	*0.346*	*0.519*	*0.751*	*0.712*	*0.954*	*0.841*

Table 5-23: Treatment average large potato count, total mass and individual tuber mass. Individual tuber mass was calculated from the count and mass data. Analysis of variance (ANOVA) and Levene's test p values are reported. Statistical significance is indicated by * and a and b groupings.

Treatment	**Average count/plot**	**Average mass (kg)**	**Average tuber mass (g/tuber)**
Control	85.0 ± 9.5 b	16.981 ± 3.54	198.4 ± 23.5
Chicken litter	95.7 ± 14.3 ab	19.452 ± 2.67	203.6 ± 6.2
12.5 t/ha vermicast	107.7 ± 3.8 a	22.812 ± 1.74	211.9 ± 15.1
25 t/ha vermicast	88.0 ± 10.4 ab	18.486 ± 2.49	209.9 ± 8.0
ANOVA p-values	*0.018**	*0.089*	
Levene's test p-values	*0.723*	*0.954*	

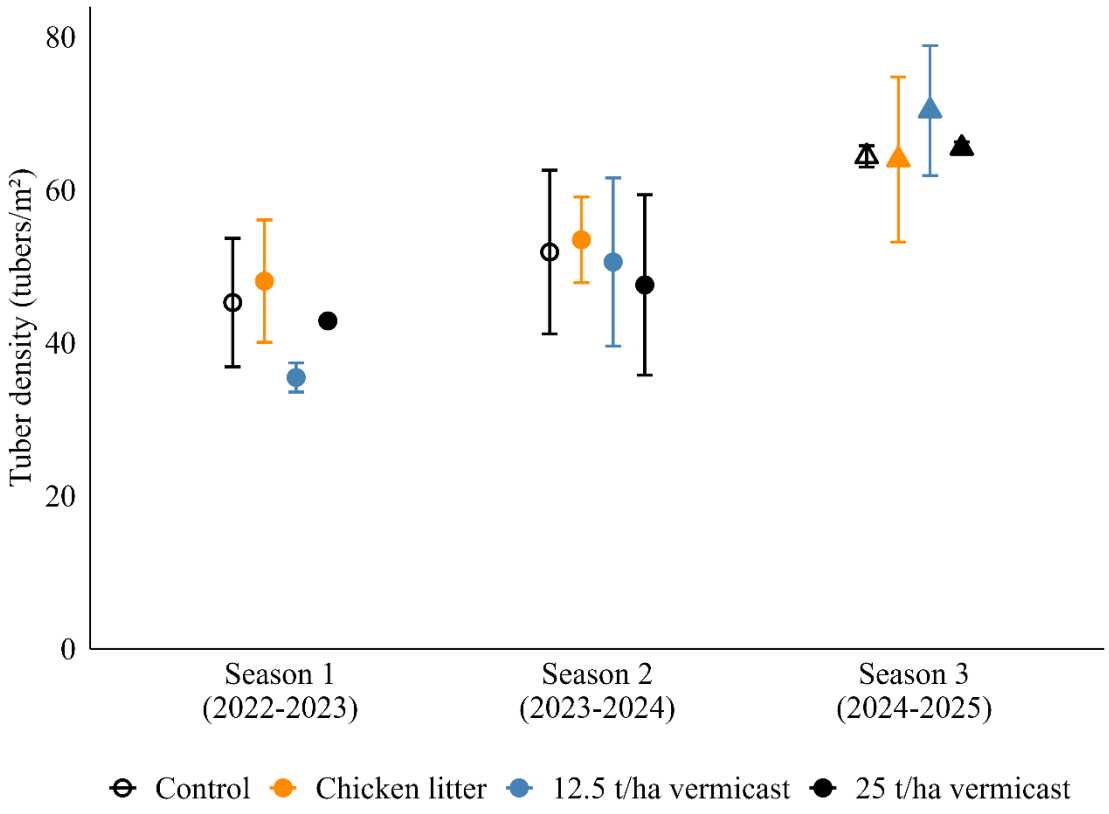


Figure 5-11: Average potato tuber density. All size classes included. Error bars are ± standard deviation. Circles are "Crop 78", triangles are "Moonlight" variety.

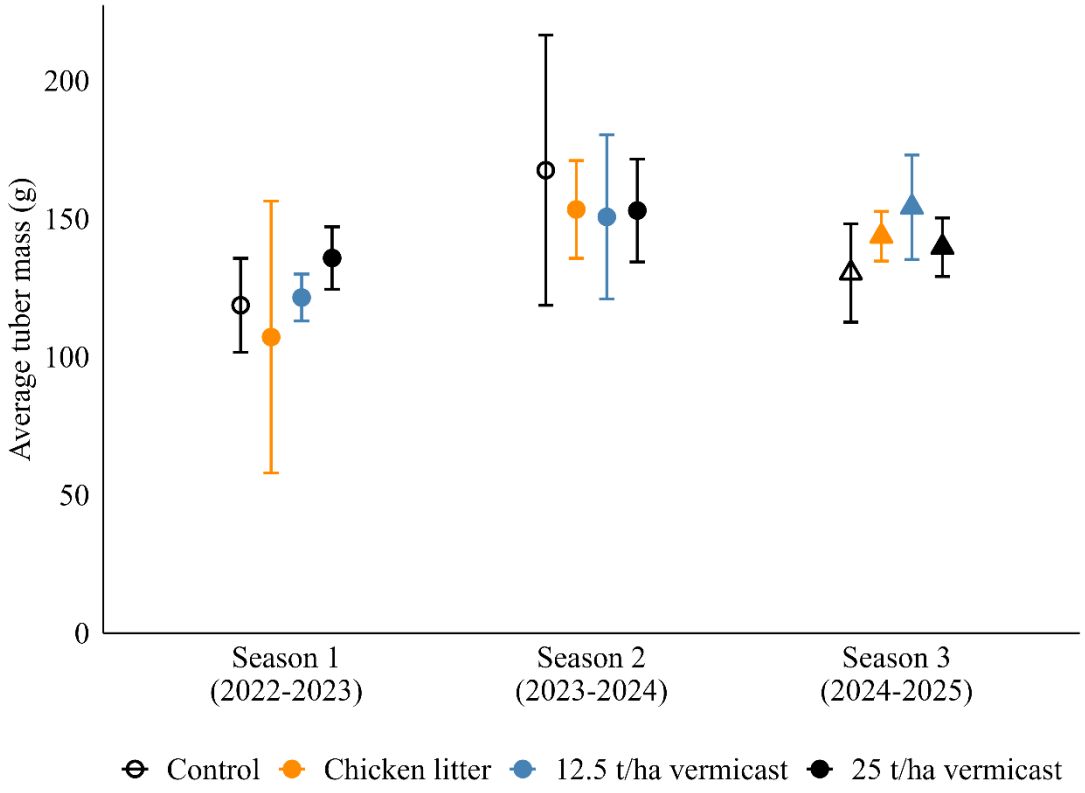


Figure 5-12: Average (calculated) potato tuber mass. All size classes included. Error bars are ± standard deviation. Circles are "Crop 78", triangles are "Moonlight" variety.

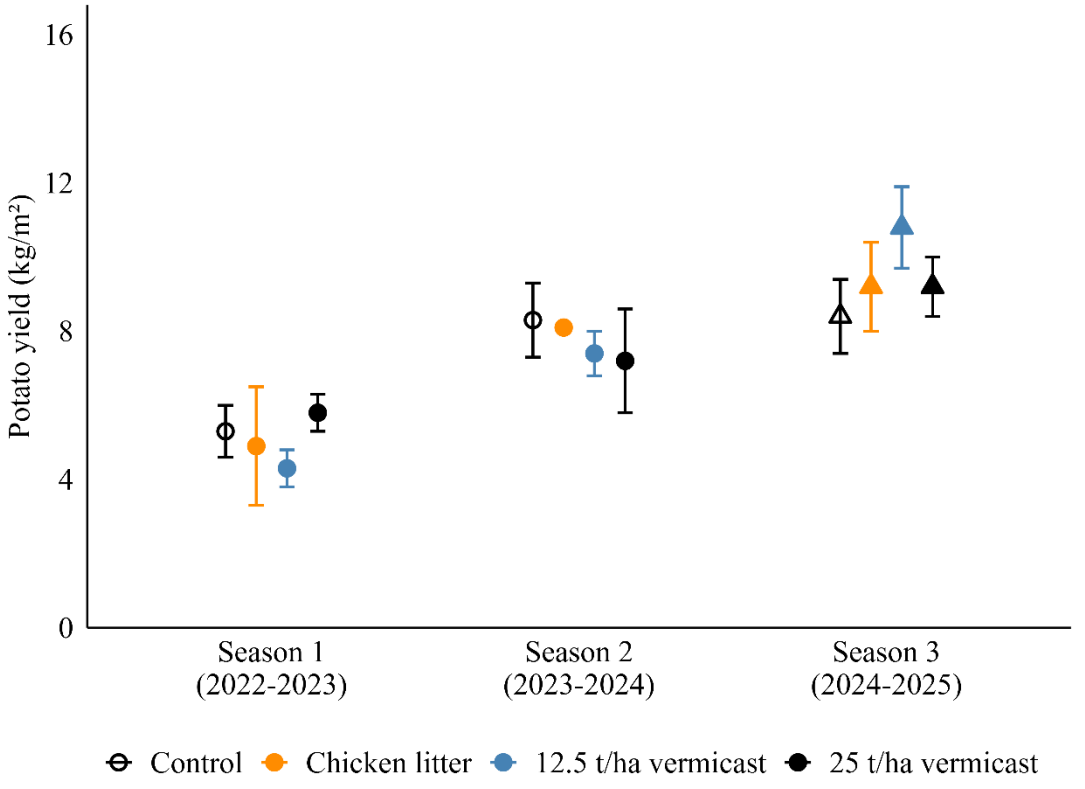


Figure 5-13: Average potato yield. All size classes included. Error bars are ± standard deviation. Circles are "Crop 78", triangles are "Moonlight" variety.

5.5.8 Maize

5.5.8.1 Yield analysis

A few factors affected the maize samples over the experimental period, meaning multi-season analyses were not possible. In Season 1 (as for all other seasons and trials), treatments were applied based on GPS coordinates. As treatments were applied ahead of sowing, the markers used for treatment application were removed and replaced using the same GPS unit after machinery had passed through. As the soil surface was disturbed during planting, the broadcast (surface applied) vermicast and chicken litter were not visible as reference points. When remarking these plots prior to seedling emergence for later cob sampling, the GPS unit switched between the preferred Matamata base station (GSMAfixedADV4) to the default Hamilton base station (GSHTfixedADV4). This change went unnoticed and caused the plots to shift about 2 m east when plotted against the trial coordinates. After sampling cobs, the pegs were removed for the commercial harvest. After commercial harvest, the plots were remarked for soil sampling. At this point, the temporary paint lines used to identify the trial during the harvest were discovered about 2 m east of where they were expected to be. A 1 m buffer (east-west direction) had been incorporated into the sampling design, but this was not enough to account for the GPS error and samples were taken across different treatments within the same row. These data were initially analysed and no differences were observed, however as they were mixed between treatments, the results were discarded and are not commented on further. This only affected the harvest of the maize plots, not the application of treatments to this trial so there would have been no effect of this on Season 2 onions or Season 3 potatoes grown in this trial location.

In Season 2, no significant differences were detected in plant density/10 m ($p = 0.705$), cob mass/100 plants ($p = 0.981$) or kernel mass/100 kernels ($p = 0.338$). A row effect was detected for cob and kernel masses ($p = 0.041$ and 0.033, respectively), but the effect was not distinguished in post-hoc comparisons, indicating a spatial gradient rather than distinct row effects. A column effect was detected for plant count ($p = 0.020$). Column B had the highest density followed by A, D and C. Season 2 power analyses indicated low power for all measurements. Plant density and cob mass had small effect sizes, though kernel mass had a large effect size and would have required fewer replicates than the other measurements to detect a significant effect, if one was present. Shapiro-Wilk p-values for normalcy of data are reported in Table 8-14. The Control returned a

significant p-value (0.031) for plant density in Season 2, though upon examination of diagnostic plots, this was attributed to low sample size (n = 4), rather than non-normal distribution.

A widespread aphid infestation of maize plants was observed at sampling in Season 2, but no effects on treatments were recorded.

No yield data are available for Season 3 as extra cobs were sampled in a number of plots across different rows and columns meaning the data were not comparable. However, plant densities, kernel mass and quality were able to be analysed. The maize in Season 3 was planned for silage so harvesting occurred earlier in the season than for grain, meaning that the DM content of the plants and their kernels was higher than for grain. This made the cobs difficult to process. Threshing (removal of kernels from the cobs) took longer than the previous seasons and it was obvious samples were drying each day. This did not affect the kernel mass analysis as all samples were dried to 60°C over 5 days.

A significant effect was detected for kernel mass in Season 3 grain ($p = 0.008$). The 25 t FM/ha vermicast treatment produced significantly heavier kernels than the 12.5 t FM/ha vermicast and Control treatments, but not the 3 t FM/ha chicken litter treatment. A column effect was detected ($p = 0.015$) where Column C grew the heaviest grain, followed by Columns A, B and D. This effect was accounted for in the trial design and did not affect treatment outcomes.

5.5.8.2 Quality analysis

The Season 1 quality analysis is not reported here for the reason given in Section 5.5.8.1. All results reported below are presented in Table 5-25.

In Season 3, the maize was destined for silage, not grain and had a very low DM content (~8.5%) as it was less mature than that harvested in the previous seasons. This made processing difficult as kernels tended to rupture during threshing, though quality analysis was still possible. As quality analyses were reported on a DM basis, the time taken to process the maize samples did not appear to impact these results (no spatial effects were detected). No significant treatment effects were detected for any quality measurements in Seasons 2 or 3. Some variables violated the assumptions of normality and homogeneity of variance (Shapiro-Wilk and Levene's tests, $p < 0.05$). However, given the small sample size (n = 4 per treatment) and inspection of residual plots, these violations were considered acceptable.

Power analyses indicated all tests were underpowered in both seasons and the resulting Type II error rate was high 46 to 95% in Season 2 and 73 to 94% in Season 3.

Depending on the test, seven to 412 replicates would have been needed to detect a significant difference at $\beta = 0.80$ in Season 2 and 12 to 222 in Season 3.

In the multi season analysis, significant differences were detected in all quality tests except for crude protein, soluble sugars, starch and non-structural carbohydrate. The difference in dry matter content was expected, as was variation in some quality parameters as the Season 3 silage maize was at an earlier stage of maturity than the Season 2 grain maize. Season 2 was higher in dry matter, metabolisable energy, N, organic matter and organic matter digestibility than Season 3, but lower in neutral detergent fibre, crude fat and ash.

Table 5-24: Average statistics for maize crops grown each season in Trials A, B and C, including analysis of variance (ANOVA) and Levene's test p values. All reported averages are ± standard deviation. Results from post hoc (actual power) and a priori power analyses (minimum replicates to achieve power of at least 0.80) at $\alpha = 0.05$ are also reported for total sample sizes of 16 and n = 4. Season 1 was excluded, as per the text. Season 2 was grown for grain, Season 3 was grown for silage. Kernel mass is after oven drying at 60°C (DM_{60} = dry matter at 60°C). *Indicates a significant effect ($p < 0.05$)

Treatment	**Plant density (count/10 m)**	**Cob mass (kg/100 cobs)**	**Kernel mass (g DM_{60}/100 kernels)**
Season 1, Trial C			
Control	NA	NA	NA
Chicken litter	NA	NA	NA
12.5 t/ha Vermicast	NA	NA	NA
25 t/ha Vermicast	NA	NA	NA
Season 2, Trial B	49.2 ± 2.6	26.9 ± 1.6	37.2 ± 0.5
Control	49.1 ± 3.5	26.8 ± 1.9	37.4 ± 1.2
Chicken litter	49.0 ± 3.7	27.1 ± 2.0	36.6 ± 0.8
12.5 t/ha Vermicast	50.5 ± 2.8	27.0 ± 0.6	36.7 ± 1.2
25 t/ha Vermicast			
ANOVA p-values	*0.705*	*0.981*	*0.338*
Levene's test p-values	*0.809*	*0.322*	*0.183*
Cohen's F	*0.220*	*0.075*	*0.399*
Power at α = 0.05	*0.086*	*0.054*	*0.182*
Type II error rate	*91%*	*95%*	*82%*
Minimum replicates required	*58*	*486*	*19*
Season 3, Trial A			
Control	64.9 ± 1.9	NA	25.4 ± 0.8 b
Chicken litter	65.8 ± 1.5	NA	26.0 ± 0.4 ab
12.5 t/ha Vermicast	67.0 ± 1.2	NA	25.5 ± 0.2 b
25 t/ha Vermicast	64.7 ± 1.5	NA	26.3 ± 0.5 a
ANOVA p-values	*0.326*		*0.008**
Levene's test p-values	*0.530*		*0.227*
Cohen's F	*0.682*		*0.860*
Power at α = 0.05	*0.473*		*0.686*
Type II error rate	*52%*		*31%*
Minimum replicates required	*7*		*5*

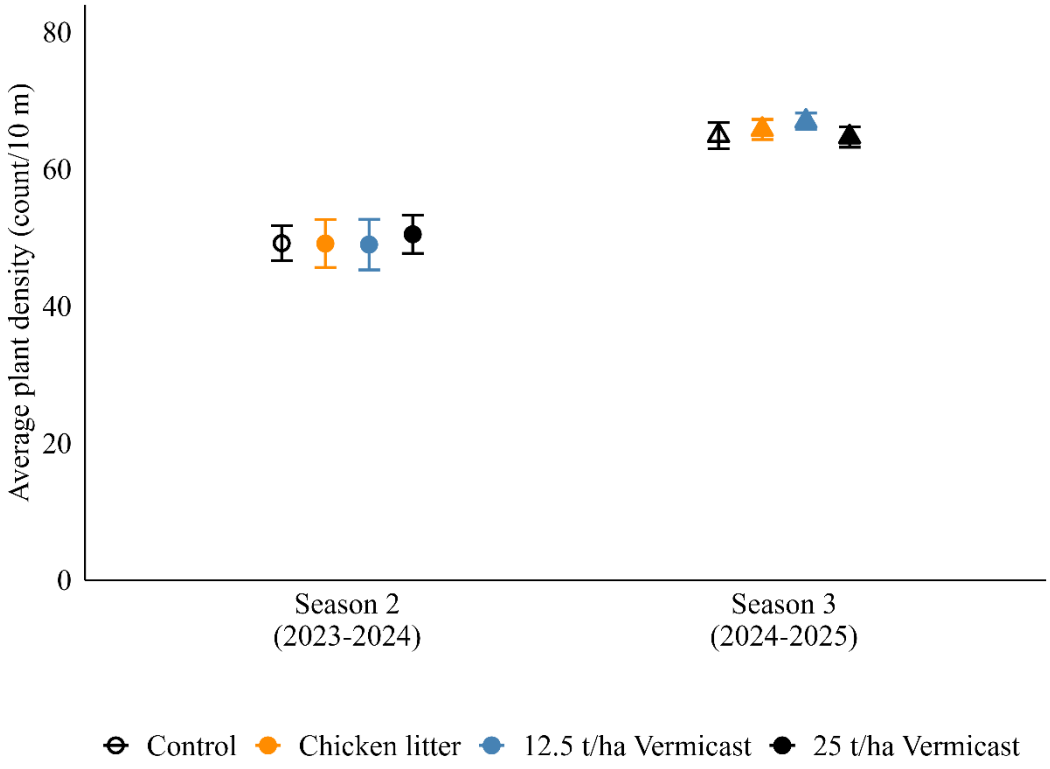


Figure 5-14: Average plant density per 10 m for Seasons 2 and 3. Season 2 was destined for grain, while Season 3 was destined for silage.

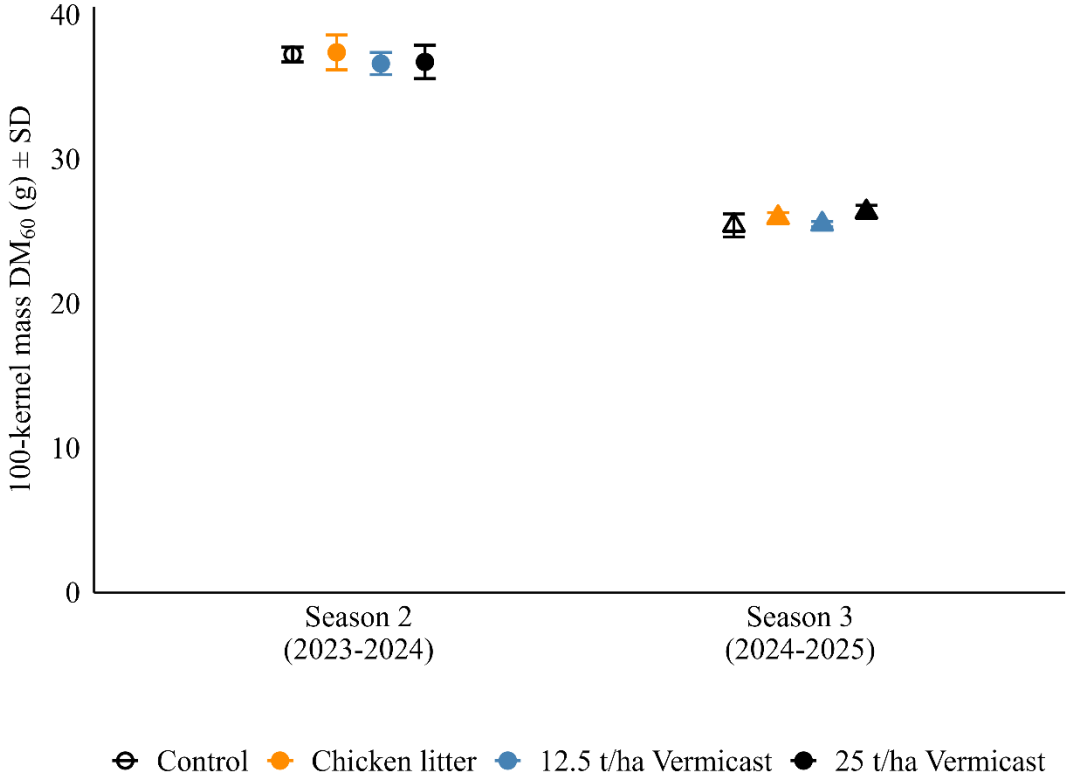


Figure 5-15: Average mass of 100 kernels dried at 60°C for five days (DM_{60}). Seasons 2 and 3. Season 2 was destined for grain, while Season 3 was destined for silage.

Table 5-25: Maize grain quality analysis results for Seasons 2 and 3. Season 2 was grown for grain and Season 3 for silage. Multi season analysis compared quality between season (treatments and replicates bulked together). Minimum replicates Values are ± standard deviation. The table is continued on the next page.

	Dry matter (%)	**Metabolisable energy (MJ/kg DM)**	**Nitrogen (%DM)**	**Crude protein (%DM)**	**Neutral detergent fibre (%DM)**	**Organic matter (%DM)**	**Ash (%DM)**
Season 2, Trial B							
Control	69.3 ± 0.6	14.1 ± 0.1	1.3 ± 0.1	8.3 ± 0.2	8.6 ± 0.4	98.7 ± 0.1	1.4 ± 0.1
Chicken litter	69.3 ± 1.8	14.1 ± 0.1	1.4 ± 0.1	8.3 ± 0.2	8.6 ± 0.7	98.7 ± 0.1	1.4 ± 0.1
12.5 t/ha Vermicast	69.4 ± 0.3	14.1 ± 0.1	1.3 ± 0.0	8.3 ± 0.1	8.1 ± 0.4	98.7 ± 0.1	1.3 ± 0.1
25 t/ha Vermicast	69.5 ± 1.0	14.1 ± 0.1	1.3 ± 0.1	8.2 ± 0.4	9.0 ± 0.6	98.8 ± 0.1	1.3 ± 0.1
ANOVA p	*0.952*	*0.815*	*0.455*	*0.858*	*0.198*	*0.650*	*0.650*
Shapiro-Wilk p	*0.029**	*0.002**	*5.27 x 10-6**	*0.724*	*0.741*	*0.028**	*0.028**
Levene's p	*0.517*	*0.844*	*0.310*	*0.025**	*0.617*	*0.330*	*0.330*
Cohen's F	*0.107*	*0.346*	*0.447*	*0.202*	*0.738*	*0.280*	*0.280*
Achieved power	*0.058*	*0.146*	*0.220*	*0.080*	*0.541*	*0.110*	*0.110*
Type II error rate	*94%*	*85%*	*78%*	*92%*	*46%*	*89%*	*89%*
Minimum replicates	*239*	*24*	*15*	*69*	*7*	*36*	*36*
Season 3, Trial A							
Control	56.3 ± 2.1	13.9 ± 0.1	1.3 ± 0.1	8.6 ± 0.5	9.4 ± 0.8	98.5 ± 0.1	1.5 ± 0.1
Chicken litter	55.9 ± 1.6	14.0 ± 0.1	1.2 ± 0.1	8.3 ± 0.3	9.7 ± 0.3	98.6 ± 0.2	1.4 ± 0.2
12.5 t/ha Vermicast	55.3 ± 2.2	13.8 ± 0.2	1.3 ± 0.1	8.6 ± 0.6	9.3 ± 0.4	98.5 ± 0.2	1.5 ± 0.2
25 t/ha Vermicast	55.8 ± 1.9	13.9 ± 0.2	1.3 ± 0.1	8.5 ± 0.7	9.0 ± 1.1	98.4 ± 0.4	1.6 ± 0.4
ANOVA p	*0.332*	*0.718*	*0.843*	*0.627*	*0.705*	*0.619*	*0.619*
Shapiro-Wilk p	*0.982*	*0.135*	*3.81 x 10-5**	*0.065*	*0.255*	*0.006**	*0.006**
Levene's p	*0.904*	*0.180*	*0.426*	*0.754*	*0.044**	*0.426*	*0.426*
Cohen's F	*0.202*	*0.326*	*0.224*	*0.275*	*0.402*	*0.342*	*0.342*
Achieved power	*0.080*	*0.134*	*0.087*	*0.108*	*0.184*	*0.143*	*0.143*
Type II error rate	*91%*	*87%*	*91%*	*89%*	*82%*	*86%*	*86%*
Minimum replicates	*68*	*27*	*56*	*38*	*18*	*25*	*25*
Multi-season p-value	*2.20×10^{-16}**	*2.00×10^{-4}**	*4.35×10^{-5}**	*0.150*	*0.003**	*0.022**	*0.022**

(Table 5-25 continued) Maize grain quality analysis results for Seasons 2 and 3. Season 2 was grown for grain and Season 3 for silage.

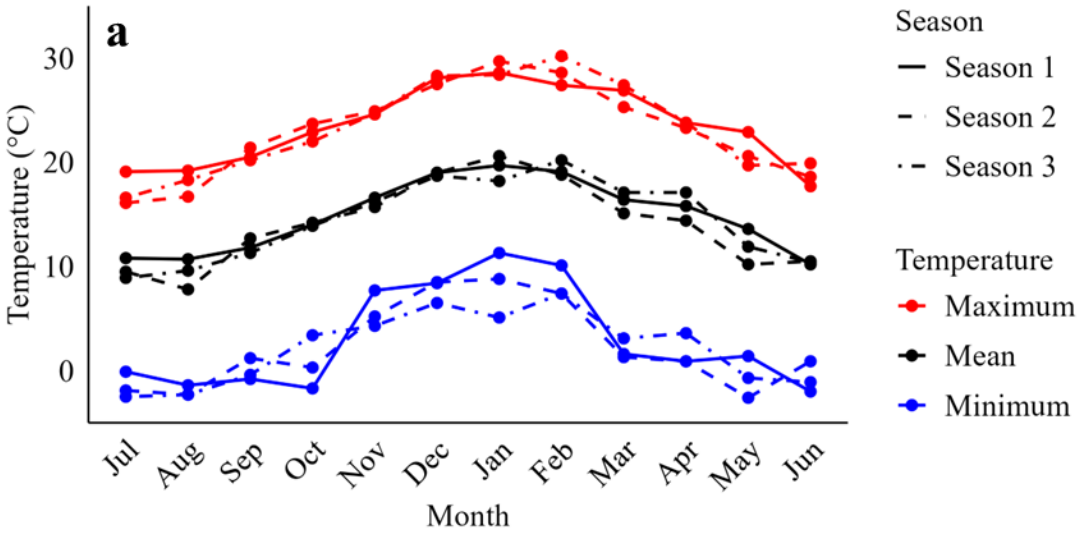
	Organic matter digestibility (%DM)	**Soluble sugars (%DM)**	**Starch (%DM)**	**Crude fat (%DM)**	**Non-structural carbohydrate (%DM)**
Season 2, Trial B					
Control	94.8 ± 0.4	2.3 ± 0.2	67.4 ± 0.7	4.0 ± 0.1	77.8 ± 0.6
Chicken litter	94.6 ± 0.2	2.3 ± 0.4	66.7 ± 0.4	4.0 ± 0.2	77.8 ± 1.0
12.5 t/ha Vermicast	94.9 ± 0.2	2.2 ± 0.3	67.6 ± 1.1	4.0 ± 0.2	78.3 ± 0.6
25 t/ha Vermicast	94.6 ± 0.2	2.4 ± 0.1	67.6 ± 0.8	4.0 ± 0.2	77.5 ± 1.1
ANOVA p	*0.410*	*0.907*	*0.483*	*0.997*	*0.596*
Shapiro-Wilk p	*0.527*	*0.165*	*0.262*	*0.267*	*0.437*
Levene's p	*0.161*	*0.132*	*0.258*	*0.593*	*0.345*
Cohen's F	*0.566*	*0.233*	*0.578*	*0.082*	*0.427*
Achieved power	*0.337*	*0.091*	*0.350*	*0.055*	*0.204*
Type II error rate	*66%*	*91%*	*65%*	*95%*	*80%*
Minimum replicates	*10*	*52*	*10*	*412*	*16*
Season 3, Trial A					
Control	94.1 ± 0.4	2.1 ± 0.2	67.4 ± 2.2	3.5 ± 0.3	77.1 ± 0.8
Chicken litter	94.4 ± 0.6	2.2 ± 0.4	67.5 ± 0.4	3.5 ± 0.1	77.2 ± 0.6
12.5 t/ha Vermicast	94.3 ± 0.5	2.4 ± 0.4	68.3 ± 1.5	3.3 ± 0.4	77.4 ± 0.6
25 t/ha Vermicast	94.3 ± 1.2	2.1 ± 0.4	67.9 ± 1.6	3.7 ± 0.2	77.3 ± 1.9
ANOVA p	*0.901*	*0.551*	*0.881*	*0.342*	*0.979*
Shapiro-Wilk p	*0.707*	*0.279*	*0.814*	*0.925*	*0.672*
Levene's p	*0.106*	*0.858*	*0.046**	*0.413*	*0.027**
Cohen's F	*0.185*	*0.374*	*0.252*	*0.507*	*0.111*
Achieved power	*0.075*	*0.164*	*0.098*	*0.275*	*0.059*
Type II error rate	*93%*	*84%*	*90%*	*73%*	*94%*
Minimum replicates	*81*	*21*	*44*	*12*	*222*
Multi-season p-value	*0.025**	*0.360*	*0.265*	*3.4×10^{-6}**	*0.070*

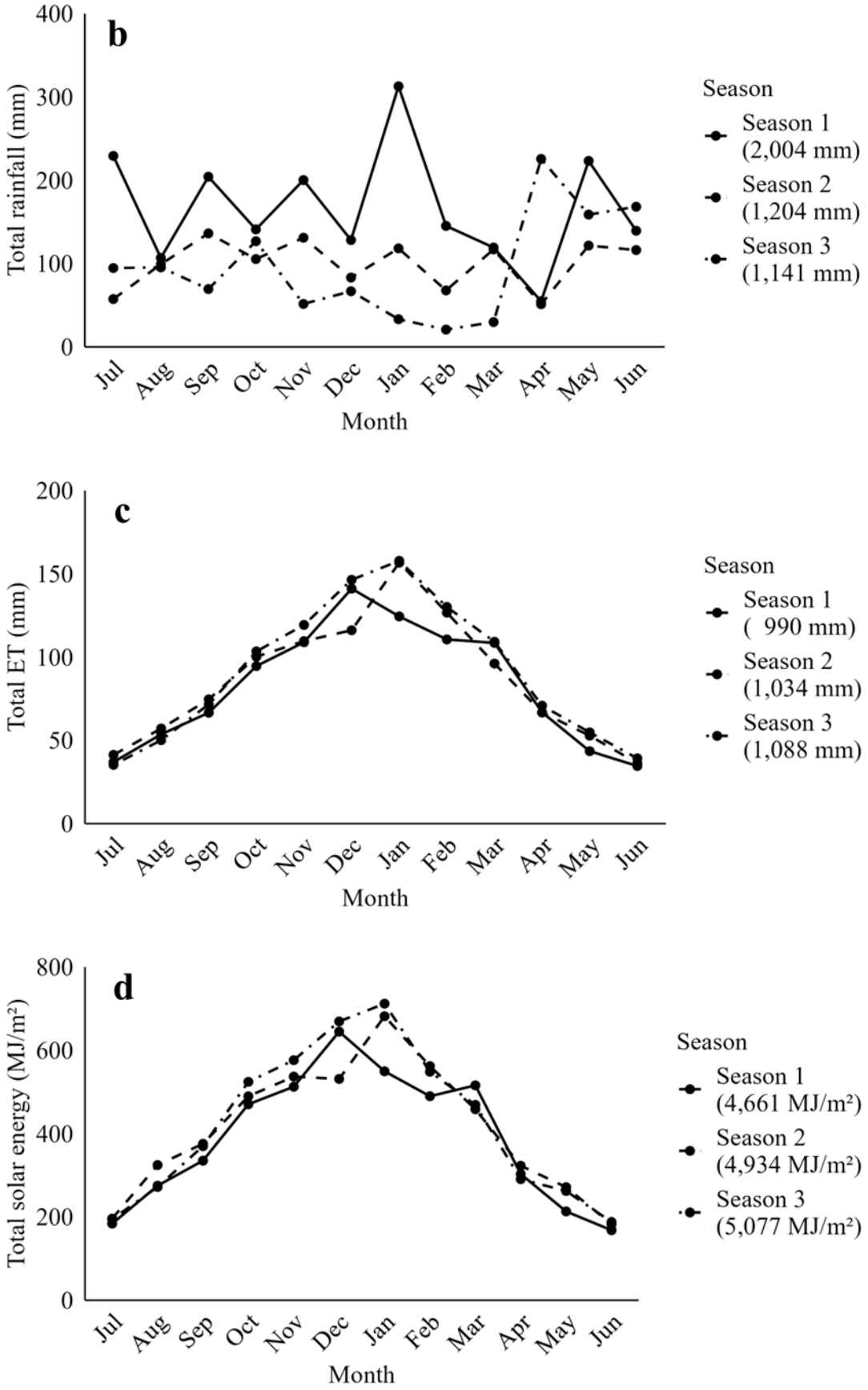
5.5.9 Weather and seasonal effects

Weather data for the three seasons are summarised by month in the following graphs (Figure 5-16a-e). Raw data are reported in Table 8-17. Notably, Season 3 had the lowest rainfall from November to March. All three crops were irrigated during this period. It appeared to have slightly higher monthly average evapotranspiration (ET) and solar energy than the previous seasons. The low rainfall would have limited growth, however irrigation was applied to onions in December of this season. Total wind run shows Season 1 to have been the windiest over the late development period (January onwards), which correlates with adverse weather (including strong wind events) that knocked developing onions over.

Average annual temperature based on 1991-2020 data for the area was reported to be 13.4°C. Annual rainfall was reported to be 1291 mm. Average temperature for the three seasons was higher: 14.8, 14.0 and 14.5°C for Seasons 1, 2 and 3 respectively. Annual rainfall in Season 1 was higher than the following seasons at 2,004, 1,204 and 1,141 mm respectively. Overall Season 1 was wetter than Seasons 2 and 3, however in January 312, 118 and 33 mm rainfall were recorded in the respective seasons.

Solar energy was similar across seasons although it was notably reduced in January of Season 1, which correlates with the higher rainfall, lower ET and increased wind run. Average temperature did not seem to be largely affected by the adverse weather.




b
Total rainfall (mm)
400
300
200
100
0
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Month
Season
Season 1
(2,004 mm)
Season 2
(1,204 mm)
Season 3
(1,141 mm)
c
Total ET (mm)
200
150
100
50
0
Month
Season
Season 1
(990 mm)
Season 2
(1,034 mm)
Season 3
(1,088 mm)
d
Total solar energy (MJ/m²)
800
600
400
200
0
Month
Season
Season 1
(4,661 MJ/m²)
Season 2
(4,934 MJ/m²)
Season 3
(5,077 MJ/m²)

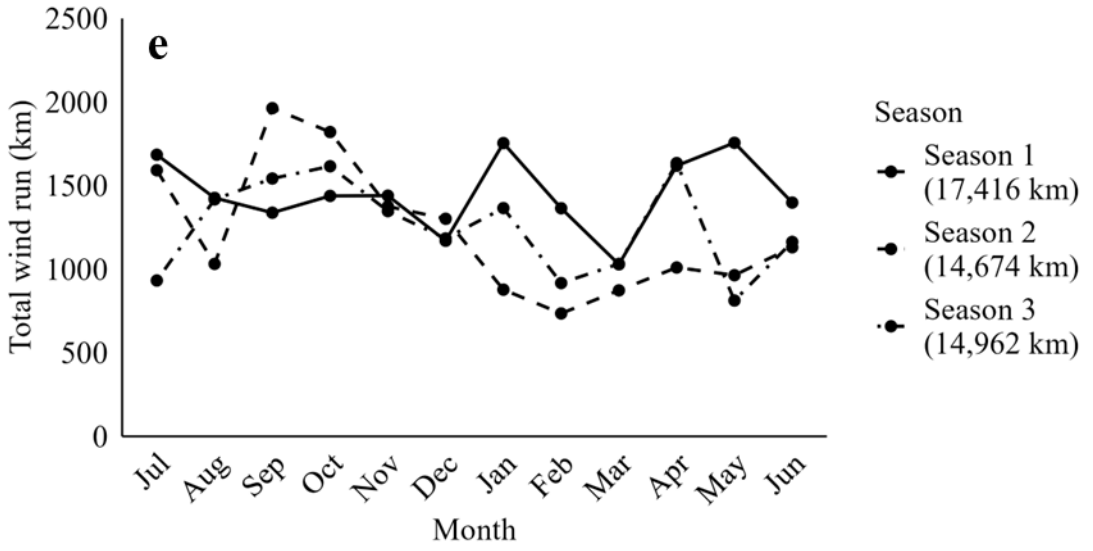


Figure 5-16a-e: Weather conditions for each of the three seasons of the Matamata field trials. Graph a = maximum, average and minimum temperature; b = total rainfall; c = total evapotranspiration (ET); d = total solar energy; e = total wind run. Seasonal totals are also reported. Data provided by MetWatch (https://www.hortplus.com/).

5.6 Discussion

5.6.1 Soils

5.6.1.1 Recent site history

Both the geological and recent site history have affected soil fertility. Geographical site history is covered in Section 5.5.1. All three trial sites have experienced similar land uses over the past few decades, however the length of time under different land uses varied. Even under the same land use e.g. dairy farming, each farm is different so management styles vary (Doole *et al.*, 2013). This could affect soil properties such as fertility and drainage. Soil type controls the inherent physical and chemical properties of soil, while management determines how these properties change over time. Allophanic soils are the most resilient soils in New Zealand, making them ideal for cropping. Trials B and C are classed as Mottled orthic Allophanic and Typic Orthic Allophanic soils. Trial A is an Acidic Orthic Gley soil. All three trial sites fell within Class 1 land use capability (LUC) (Manaaki Whenua, n.d.). Class 1 LUC contains New Zealand's most versatile and productive soils (Lynn *et al.*, 2009; Rutledge *et al.*, 2010). The versatility of the LUC has been explored and is seen in the variety of recent land management (dairy farming and cropping of asparagus, maize, potatoes, and onions). While the soils fall under Class 1, cultivation and fallowing are common practices in market gardening, both of which reduce soil organic matter content (Rasmussen & Collins, 1991).

5.6.1.2 Soil heterogeneity

Soil pH between the three trials was not homogenous, despite their proximity (<1 km between sites). Each trial was conducted on a different soil type, had recently grown a different crop to one another and been managed differently historically. It was not possible to determine what effect pH could have had on nutrient availability and plant growth as soil pH cannot be used to generalise nutrient availability across different soil types. Plants also alter the pH of their rhizospheres, affecting soil in the immediate vicinity, through nutrient uptake and the associated release of H^+ and OH^- to balance cation/anion uptake. This process can acidify or alkalise the rhizosphere, but this may not typically affect overall soil pH (Barrow & Hartemink, 2023; Hartemink & Barrow, 2023).

Sodium, P, Mn and Cu were significantly different between the three trials. Of these four nutrients, only P is a major plant nutrient. Total elemental content is not a measure of available nutrient as other factors affect nutrient availability. For example, allophane (identified in all trial sites) is known to limit phosphate availability (the form of P that plants can take up) (Bolan, 1991). While there is a difference in total P between the trials, this does not necessarily correlate to P availability. As P is a major plant nutrient, it is also regularly applied as a fertiliser to crops to optimise production. Differences in P content may in fact reflect recent fertiliser additions.

Trial B had almost half the Mn of Trials A and C. Manganese in soils originates from parent materials and is affected by weathering (Aubert & Pinta (Eds.), 1977). It can be applied to soils as a fertiliser, but as it is a trace element this is not commonly done. It is also not listed in analyses of the (commonly applied) fertilisers used over the duration of the experiment. It is more likely Mn differences are due to geographical site history.

Trial C had less Na than trials A and B. In excessive quantities, Na impacts soil structure and fertility and subsequently plant health as it can displace larger cations such as Ca^{2+} and Mg^{2+} (Black & Abdul-Hakim, 1984). Neither total Ca nor Mg were significantly different in any of the three trials.

Copper content in Trial B soils was lower than in Trials A and C, but all reported results were considered low. At 0.06-0.08 mg/kg DM, Cu was well below average concentrations (~20 mg/kg DM) for arable soils in the Waikato Region (Waikato Regional Council, 2026).

Environmental gradients were found across columns and rows in the three trial locations. This represented the dominant source of variation within trials. The results of the ANOVA analyses for soil pH and nutrients showed that the Latin square design used on all three trials overcame heterogeneity. Even when there was a significant row or

column effect because each treatment was represented once in every row and column all were treated equally.

5.6.1.3 Initial and final soil comparisons

As the final soil samples were taken at a different time of the season to the baseline samples (at harvest vs at sowing of the crop), within season activities could have influenced these results e.g. all fertiliser applications for the Season 3 onion crop contained P. This is likely given the effect was equal across all treatments.

Organic matter addition to soils is known to improve plant production (Blouin *et al.*, 2019). The increase in soil C% was equal between treatments. Prior to the baseline sampling of Trial B, the soil had been cultivated. At the final soil sampling, the onion crop had recently been harvested, leaving the soil and remnant onion roots intact. While it is possible that onion root production increased under the 25 t FM/ha vermicast treatment, the addition of vermicast itself may also have contributed to the increase in soil C%. In Season 3, about 1.8 t C/ha was added to the soil at sowing in the form of vermicast in the 25 t FM/ha treatment. Half this was added in the 12.5 t FM/ha vermicast treatment and 0.61 t C/ha was added via the chicken litter treatment. While this is a direct addition of C, the vermicast and chicken litter were surface applied, leaving them exposed to wind and water erosion. This is similar to fallowing, a practice that negatively impacts soil C as exposed soil aggregates are broken, exposing previously protected organic C to microbial attack (Rasmussen & Collins, 1991). The C% content of soils in Trial B is ~3.5%, which is considered low for an allophanic soil (a 4% threshold is reported as normal, 3% is considered depleted). Soils under annual cropping are reported to have the lowest C% at a median of 5% compared to other land uses in New Zealand (Waikato Regional Council, 2015). These results indicate the C% content of Trial B was on the low side for both soil type and land use at the start and the end of the three-year experiment.

Overall, there is not enough evidence to suggest that vermicast had a beneficial effect on onion root production. However, as root production was not directly measured, this could be an area to investigate in future studies.

5.6.2 Vermicast and chicken litter

5.6.2.1 Nutrients

While the chicken litter had a higher C% than the vermicast (44.3% vs 15.3%), the vermicast supplied 50-200% more carbon to the soil at 12.5-25 t FM/ha. The application of vermicast at each rate supplied about 917-1,834 kg C/ha while at 3 t FM/ha,

the application of chicken litter supplied 612 kg C/ha. Addition of C to soil, especially under cropping management may provide benefits to soil health, though reducing tillage has far greater benefits for soil C than the addition of organic materials (Powlson *et al.*, 2012).

The vermicast and chicken litter were quite different materials though their DM contents were similar. The vermicast averaged about 43% DM while the chicken litter averaged about 49% DM with the vermicast DM being more variable between seasons. The vermicast had a more neutral pH than the chicken litter, though it was slightly alkaline and this may in part be due to the inputs. The chicken litter pH increased between Season 2 and 3 although it had been collected at the same time (left over Season 2 chicken litter was stockpiled for Season 3). Although the vermicast was more neutral, it appeared to cause soil pH to increase in Seasons 2 and 3. This is supported by published literature (Walia & Kaur, 2024). Chicken litter is also recognised to increase soil pH (Lin *et al.*, 2022), which is unsurprising given its generally alkaline pH. The fact that only vermicast increased pH may be due to the larger quantity applied to the soil. Season 1 may not have shown an effect due to the late timing of the application and/or there may be a cumulative effect of the application of vermicast/chicken litter to soils.

Chicken litter is recognised to supply relatively high levels of C, N, P, K, Ca, Mg and micronutrients. It has also been shown to increase plant P and K uptake, but reduce N uptake, although the authors of the meta-analysis these results came from acknowledge that most data are from cotton crops (Lin *et al.*, 2022). Nitrogen losses through NH_3 volatilisation are reported to be higher than those from composted (stabilised) litter. While N supply of chicken litter can be beneficial to plants, if it is volatilised rather than mineralised or nitrified for plant uptake as NH_4^+ or NO_3^-, N can be lost to the environment instead of supplying plants (Brinson *et al.*, 1994; Sharpe *et al.*, 2004). However, if applied ahead of rainfall or irrigation events, NH_4^+ from chicken litter can be transported into the soil matrix, where it can be taken up by plants (Sharpe *et al.*, 2004). Subsurface applications or methods that incorporate chicken litter into the soil rather than broadcasting (surface application) can reduce ammonia volatilisation by 67-88% depending on the cultivation method used (Pote & Meisinger, 2014). In this study, chicken litter was broadcast on onion and maize crops, but incorporated into the soil in potato crops. The potato crops would likely have received a greater N supply than the maize and onion crops as volatilisation would have been reduced. However, NH_3/NH_4^+ toxicity zones arise from chicken litter applications and can adversely affect root development (Pan *et al.*, 2016). However, the study these results come from used a 5.1 cm

layer of chicken litter buried under 11.4 cm of soil and tested the effect on faba beans. As the chicken litter applied to the potato crops in this thesis was thin (did not fully cover the entire plot area) and subsequently incorporated into the soil, it is unlikely that the chicken litter damaged potato roots, though this was not directly studied.

Chicken litter applied to crops mainly to supply N can result in excess application of other nutrients such as P (Sharpley *et al.*, 1994), which can lead to environmental degradation if applied seasonally, allowing excess nutrients to accumulate. Quantities of nutrients applied were compared between 3 t FM/ha chicken litter and 12.5 t FM/ha vermicast on a kg nutrient applied/ha basis. For major nutrients, the chicken litter supplied about 10 kg/ha more N and 8 kg/ha more S than the vermicast, though S was detected below QL for both vermicast and chicken litter so this result should be interpreted cautiously. At 12.5 t FM/ha, the vermicast supplied about 13 kg P/ha, 387 kg Ca/ha and 1 kg Mg/ha more than the chicken litter. Potassium was detected below QL for the vermicast, but the vermicast appeared to supply more K than the chicken litter.

The vermicast contained relatively high Al concentrations about 8,452 mg Al/kg DM. However, this was less concentrated than the ~30,000 mg Al/kg DM that already existed in the top 150 mm soil of the three trials. As there was a beneficial effect of the 25 t FM/ha vermicast treatment on onions in the third season, the Al content of the vermicast was not excessive.

Chicken litter is also recognised to have a high EC (Ravindran *et al.*, 2017). The study by Ravindran *et al.* (2017) reported chicken litter from ten locations across South Africa had ECs of 2.45-12.30 dS/m. The extraction method used a 1:10 ratio of chicken litter:water and a one-hour extraction before determining pH and EC. The methodology in this thesis used a 1:5 extraction on fresh samples. Though not explicitly stated, it appears the authors tested pH and EC on air-dried and ground samples. Although the air-dried extraction would have used more chicken litter on a DM basis (more total solids extracted), the dilution was greater for the air-dried samples. This may partially explain the lower ECs in the study by Ravindran *et al.* (2017) compared to those in this thesis.

5.6.2.2 Pathogen management and risks in alternative fertilisers

Pathogen levels were not monitored in the chicken litter applied to the trials. Although chicken litter is a popular alternative fertiliser, it is known to contain faecal pathogens, which can be a risk to food production (Chen & Jiang, 2014). It is interesting to note that poultry industry practices do not align well with New Zealand horticultural standards for the application of treated manures in the *Guidelines for Fresh Produce Food*

Safety 2019. For example, "ageing is different to composting, as it simply involves leaving the material in a static pile for an indefinite period. Depending on temperature and environment, at least six months of ageing is needed to significantly reduce microbial populations" (Fresh Produce Safety Centre Australia & New Zealand, 2019). Microbial populations were not analysed in the vermicast or chicken litter in any season. The chicken litter in Season 3 was the stockpiled leftovers from the Season 2 applications. Given the Season 3 chicken litter had more than 6 months of ageing prior to application, it may have had reduced microbial populations, including pathogens. In contrast to stockpiling, vermicomposting is recognised to significantly reduce pathogens e.g. (Eastman *et al.*, 2001). While pathogen reductions were not measured in the vermicomposting trials in Chapter 3 of this thesis, these trials showed *E. coli* was <2 MPN/g in the finished vermicomposts i.e. less than the default detection limit of 2 MPN/g. The inputs for this trial were chicken processing DAF sludge (a by-product of broiler (meat chicken) processing plants) and cardboard. As the DAF sludge is produced at a food processing facility with high hygiene standards, it is anticipated to have lower pathogen counts than chicken litter from broiler (meat chicken) farms.

Based on the information in the 2019 Guidelines report and personal communication with industry members, stockpiling (ageing) is uncommon in New Zealand, except in summer and winter months when it is either too dry or too wet to apply litter (Kerry Mulqueen, personal communication, November 11, 2022; Graeme Rodley, personal communication, November 4, 2022). Summer stockpiles may tend to be applied to land in the autumn when it is cooler and wetter, and winter stockpiles in the spring. Only stockpiles created at the beginning of summer/winter and applied at the end of autumn/spring respectively could achieve six months of ageing. Given the demand for chicken litter, particularly in the springtime, achieving six months of ageing is unlikely. This means that growers purchasing even stockpiled chicken litter should consider the risk of pathogens as there is a still a risk that "some human pathogens may still survive in cooler areas of the pile" (Fresh Produce Safety Centre Australia & New Zealand, 2019).

5.6.2.3 Weeds in vermicast

Weeds were present in the vermicast and were introduced to the trial area. One of these was fathen (*Chenopodium album*), a highly competitive cropping weed in New Zealand (Massey University, n.d.) which is already managed on the site. Although weeds are undesirable, providing they are not new to a site or unmanageable, this may not be an issue for producers. Regardless, dispersal of weed seed is undesirable and if products are

known to contain weeds, it would be better to utilise local sources to minimise spread of species between regions.

5.6.3 Onions

5.6.3.1 Onion production

Vermicast and chicken litter were not applied near sowing in Season 1 as the experiment began after onions were sown. Onions were sown on August 4, 2022. Vermicast was applied on October 18, 2022, when the onions were about 150 mm tall. Chicken litter was applied on October 27, 2022. Neither vermicast treatment nor the chicken litter treatment had an effect on onion performance in the first season, although an effect was anticipated. The lack thereof was partially attributed to the timing of treatment application. To investigate this further, a glasshouse trial was conducted in parallel to onions grown in Season 2 (see Chapter 4). The trial investigated the timing of the application of vermicast to onions grown from seed on the same soil and under the same fertiliser management. No differences were detected and this was attributed to high temperatures limiting growth and low power. The trial was repeated the following year on another soil under glasshouse conditions. This trial also showed no effect of the timing of vermicast application to onions, though it again was underpowered.

It is unlikely that there was a significant difference between treatments in Season 1 due to the small effect sizes, but this cannot be confidently confirmed due to the low power. Low power was also found in Season 2, though it showed larger effect sizes and more power than Season 1. It is possible Type II error occurred in the analyses and that treatments did have an effect. Chicken litter was found to have significantly reduced onion density in Season 2, though no effect was found for onion mass or yield.

Higher onion densities were noted to correlate with lower average onion masses. Size proportions in Seasons 1 and 2 were similar across treatments, indicating environmental factors affected onion size more than the treatments. In Season 3, there was more variation between treatments, in contrast to Seasons 1 and 2. In Season 3, most onions fit into the small and medium categories. The size distribution of onions between size classes varied between treatments, with chicken litter producing bigger but fewer onions and lower overall yield. This is corroborated by Jilani (2010) who showed that greater spacing (up to 200 x 100 mm) produced onions with higher average bulb mass and size, and lower overall yield, compared to closer spacings (75 x 75 mm). However, in the widest spaced treatments, they also reported greater numbers of ‘multiplier bulbs’ (a quality defect) that would negatively affect storage ability and not meet consumer

requirements. Multiplier bulbs were not observed in this trial. While other factors such as trial location, management and overall weather conditions influence onion growth, Season 2 produced significantly larger onions than Season 1. Onion density was highest in the first season, though apparently not above target densities for the cultivar. Excessively high densities established at sowing, could have compromised onion mass due to competition (Jilani, 2010).

Chicken litter had significantly lower density than the Control in Seasons 2 and 3. The significant interaction between treatment and season in onion density may have been due to an effect on germination, seedling development and/or disease pressure. Initially, it was hypothesised that NH_3/NH_4^+ burn was caused due to applications made close to sowing. Sowing in Season 2 occurred on 18 August 2023 while chicken litter and vermicast were applied on 24 and 25 August 2023 (six to seven days post sowing). A total of 13.6 mm rainfall occurred on 30 and 31 August 2023. In Season 3, onions were sown on 26 July 2024 and vermicast and chicken litter were applied on 7 August 2024 (11 days post-sowing). A total of 6.8 mm rainfall was recorded the following day with showers in the following four days. Based on data from Brinson *et al.* (1994) and Sharpe *et al.* (2004), it is plausible that rainfall following chicken litter application converted volatilised NH_3 to NH_4^+ and moved it into the soil. If localised NH_3/NH_4^+ concentrations were sufficiently high near emerging seedlings, toxicity could have contributed to mortality and reduced density. Although chicken litter significantly reduced density in Season 3, yields across all treatments (including the control) were reduced in this season. Also, in Season 1, chicken litter was applied to approximately two-month-old onion seedlings and had no detrimental effect. Although the trial was underpowered (false negatives may have arisen), the effect size of density was small indicating there likely was little to no effect, regardless of power. In summary, the causes of the reduction in onion density for chicken litter treatments in Seasons 2 and 3 were not confirmed, though NH_3/NH_4^+toxicity may have contributed.

The cost-benefit analysis and sensitivity analysis showed promising potential for the 25 t FM/ha vermicast treatment in Season 3 where yields[8] were increased by a 9.1 t/ha (based on a 1.6 kg/m^2 difference between the Control and this vermicast treatment). The vermicast treatment was calculated to have produced a total yield of 57.7 t/ha, compared to 48.6 t/ha for the Control. These are lower than, but comparable to yields of Pukekohe long keeper (71 t/ha) and early long keeper (62 t/ha) varieties achieved by Hutton and

[8] The yield/ha values were calculated from a very small relative area (11 x 1 m^2 subplots x 4 treatment replicates = 44 m^2 total area = 0.0044 ha).

Wilson (1986) on desirable cropping soils in the Pukekohe region. The authors trialled a different variety of onions to the Rhinestone variety in these trials and they also grew the onions at lower planting densities of 83 onions/m^2. Planting densities (based on total onions harvested/m^2) in Season 3 were 75.4 onions/m^2 for the Control and 88.0 onions/m^2 for the 25 t FM/ha vermicast treatment. Ideally yield increases would not be due to an increase in the number of pickling bulbs as opposed to marketable sizes. There was no evidence of the vermicast treatment increasing the proportion of picking bulbs relative to the Control.

The financial benefit of the additional 9.1 t onion/ha was $812/ha. Under sensitivity analysis, this held up under 20-50% increases in the cost of purchasing, transporting and spreading vermicast from Kinleith (the nearest vermicast dispatch centre to the trial site). It only became unfeasible when the yield increase was reduced to 6.7 t/ha and profit of $250/t onions was reduced by 50%. Other factors that need to be considered are potential challenges in weed control – this may not be an issue on farms already managing weeds as cultivation and spray programmes can manage common weeds. However, if a new species was introduced and required additional management such as specialised herbicides, this may affect operating costs and therefore financial viability. The sensitivity analyses did not directly account for variations in yield due to soil heterogeneity, however the $200/ha minimum value of vermicast application at a total yield increase of 6.7 t onions/ha indicates that soil variation causing yield reductions may not be an issue.

A final note on the value of vermicast in providing a financial benefit is the potential for it to be used to offset fertiliser costs. The vermicast analyses indicate it supplies large amounts of major plant nutrients such as P. There may be potential to use vermicast as a supplement to diammonium phosphate fertilisers on onion crops, for example. Soil Olsen P contents from onions grown under glasshouse conditions with 75% recommended P (as DAP) were the same as the Control treatments receiving 100% recommended P (Chapter 4). If fertiliser applications were able to be reduced by 25%, this would provide additional benefits to growers in financial savings as well as reduced reliance on imported rock phosphate fertiliser derivatives.

5.6.3.2 Environmental factors

Multiple factors may have affected the onion trial outcomes. These include low power, delayed treatment application (Season 1), weather conditions, age of vermicast and trial location/soil type. These are discussed below.

The baseline soils in Trial A showed that Column A had a significantly higher Na concentration than B, C and D. Trial A also grew the lightest onions in Season 1. Excess Na is known to stress plants, including onions (Wannamaker & Pike, 1987). However, only elemental Na content was measured in this trial and this does not indicate the potential to damage soil structure e.g. (soil sodicity) or plants. Excess wilting was not observed in Column A during the trial. Sodium content did not necessarily affect onion growth, however higher levels correlated with lighter onions within Trial A.

An alternative explanation for the lighter onions is the presence of a tramline within Column A. In Season 1, the tramlines were formed several metres from their planned location, meaning the trial was not designed around their actual position that season. As a result, fertiliser and spray machinery traversed Bed 2 throughout the growing period, which may have affected onion production in this area. As all treatments were replicated once in each Column, there was no confounding effect of tramline placement.

In addition to the within trial soil variation, the three trials differed from each other. Even though they were located within 1 km of each other, they had different properties (e.g. drainage and topsoil depths) due to formation processes. They had similar recent land use histories, but each trial was part of a different farm until Trial C was incorporated into the current farm for maize, potato and onion production. Both land use and soil type affect crop performance (Lynn *et al.*, 2009).

A strong wind event in Season 1 prematurely folded onion tops over about 2-3 weeks before lifting was anticipated. This may have influenced overall onion development and therefore yield for Season 1 (this was the windiest season over the late growing period). Maximum recorded wind gust was 20.6 km/hr from a north easterly direction on 4 January 2023. Mean wind speed on this day was 6 km/hr. The strength of the wind event may not have been well recorded as the weather station the data was obtained from is located in a relatively sheltered site compared to the open fields where the trials were conducted.

Season 3 had the lowest rainfall from November to March (most of the onion growth and development period). While onions were irrigated in December, this may not have been enough as Season 3 had the lowest overall yields. Water stress may have limited growth and weather conditions/stressed plants may have increased disease pressure. One soil-borne cropping disease, *Fusarium oxysporum* (basal rot), was observed at harvest in Season 3. It is a slowly progressing disease that begins as an infection in the base plate (where the growing point is located) and eventually rots the bulb, affecting quality (Currah *et al.*, 2012). The bulbs had not rotted, rather the disease was detected as

an abnormal (dry) growth at the basal plate. It was observed more frequently in the 25 t FM/ha treatment (4.0% of individually assessed onions) than the other treatments (2.1-3.5%), but this was not statistically significant (although the test was underpowered). Growth and spread of this particular fungus is favoured at higher temperatures (Currah *et al.*, 2012). From November to February, minimum monthly temperatures were lower in Season 3 compared to Seasons 1 and 2. In February, maximum temperatures were slightly higher in Season 3, however, the average monthly temperatures do not appear to deviate strongly from the previous two seasons. As Fusarium oxysporum growth and spread is favourable at higher temperatures, the summer months are likely to be high risk. While no specific literature was available on the potential for vermicast or other vermi products such as vermicomposts or extracts was available, vermi products are well known to suppress plant diseases (Yatoo *et al.*, 2021). Presence of this disease may provide part of the answer for reduced onion vigour in all Season 3 treatments. Its presence may be related to the trial location, weather and/or management.

As well as *Fusarium oxysporum*, *Pectobacterium carotovorum* (bacterial soft rot) may also have been present in Season 3. Bacterial soft rot presence was not recorded at harvest, but bulbs cut open after the trial completed showed signs of this disease (rotten individual leaves/layers of the onions) (Currah *et al.*, 2012). Treatment effects were not detectable at this point as the onions were mixed. This disease was not detected in harvested onions in the previous trials. Though no formal analysis is possible, this indicates Season 3 likely had higher disease pressure than the previous seasons. A meta-analysis by Blouin *et al.* (2019) proposed that exposure of crops to pests and diseases in field trials may be more likely to demonstrate beneficial impacts of vermicomposts compared to control treatments, as may be the case in Season 3.

5.6.4 Potatoes

Neither chicken litter nor vermicast had an effect on potato yield or quality in any season. This could have been due to low power, which was compounded by missing data in Season 1 and 3. The variety changed in Season 3 as there were not enough Crop 78 seed potatoes to plant the trial area. Instead, another French fry variety (Moonlight) were sown. In Season 3, overall average yields were higher and this may be attributed, in part, to variety as Moonlight's is classed as high-yielding (Anderson *et al.*, 2004).

While no treatment effects were able to be detected in any season, two column effects were detected in Season 3. Column B had fewer large tubers than Column A and lower specific gravity than Columns A and C. This relationship (lower specific gravity

with smaller tubers) is supported by the findings of Meena *et al.* (2016). Hollow heart, a physiological disorder where a cavity forms in the pith of the tuber, was considered as a cause. Hollow heart can be caused by nutritional or moisture stress and affects marketability of tubers (Rex & Mazza, 1989). Nylund and Lutz (1950) reported that the incidence of hollow heart tended to be greater in tubers with lower specific gravity. They also reported that larger tubers tend to be more susceptible. Although, specific gravity can indicate hollow heart, the authors concluded it was an impractical method of determining the presence of the defect. Short of cutting tubers open, x-ray is more practical method of detecting the defect (Rex & Mazza, 1989).

For sugar testing of Moonlight in Season 3, cross sectional slices of large tubers (>60 mm diameter) were taken from the centre of tubers for fry testing (a commercial measure of reducing sugar content). Due to the destructive nature of the fry test, hollow heart would have been detected in the large tubers analysed. The lack of hollow heart in the 80 tubers tested across the 16 plots indicates that this was not likely an issue in Season 3, although it was the driest season. Irrigation management (December 2024 – March 2025) and variety (Moonlight does not tend to be susceptible to hollow heart (Anderson *et al.*, 2004)) may have alleviated the potential incidence of hollow heart in Season 3.

Quality was analysed in the Moonlight variety/Season 3. Sampling and analysing potatoes close to commercial harvest to mimic commercial activities was important in this study. Longer growing periods prior to harvest have been shown to affect tuber yield and quality by increasing yield, DM and starch contents (Sharkar *et al.*, 2019). Early research proposed reducing sugar (glucose and fructose) and sucrose contents together were key characteristics that affect potato chip colour upon frying (Shallenberger *et al.*, 1959). However, later studies suggest appears to be variety-dependent and do not always predict fry colour (Pritchard & Adam, 1994). Environmental factors such as storage temperature of potatoes affects their reducing sugar contents and subsequently chip colour upon frying. In fry-testing, the Maillard reaction between reducing sugars and amino acids at high temperatures causes non-enzymatic browning of chips (Shallenberger *et al.*, 1959). This also causes a bitter taste (Kumar *et al.*, 2004). In this research, though some chips appeared more brown after frying than others, no differences were detected in overall whiteness of the Moonlight chips after frying. This may, in part be due to low trial power. However, there is also evidence that fertiliser nutrition does not necessarily affect reducing sugar content (Kumar *et al.*, 2004). A recent study also showed that vermicompost improved starch contents of potato tubers, but also increased reducing

sugar contents (Ferdous *et al.*, 2019) which would likely be detrimental in tubers destined for chip processing.

5.6.5 Maize

To increase the quality value of maize silage (and grain), the focus is on the grain component as it contributes 80% more energy to silage products than the leaf or stem do (Densley *et al.*, 2004). Although broadcast vermicompost has been shown to benefit maize grain yield at 6 t/ha (though less than recommended fertiliser rates) (Tekulu *et al.*, 2025), no significant differences were detected for any grain quality parameters in Seasons 2 or 3. Significant differences were detected between Seasons 2 and 3 in dry matter, metabolisable energy, N, organic matter and organic matter digestibility, neutral detergent fibre, crude fat and ash, likely reflecting differences in maturity. The grain from Season 3 was sampled the day before the planned commercial harvest, however the commercial harvest did not occur for another few weeks after the sampling date. This reflects the contractors' dependencies on weather, filling supply contracts and variability in resource allocation. The maize grain in Season 3 was noticeably wetter than the previous two seasons which affected the integrity of kernels threshed for analysis and many were damaged. However, from the DM_{60} 100-kernel mass analysis, it was clear that the 25 t FM/ha vermicast treatment produced heavier grain.

A study by Hirzel *et al.* (2007) showed that nutrient supply, yields and nutrient uptake of maize silage were similar amongst chemical fertiliser only treatments and 10-20 t/ha poultry litter treatments applied with and without the addition of N fertiliser. The chicken litter treatments applied in this research were at much lower rates (3 t FM/ha), though they were applied on top of normal crop fertilisers, not just the addition of N fertiliser. It was not possible to analyse yield data in Season 3, though chicken litter did not appear to have an effect on kernel grain mass, unlike the 25 t FM/ha vermicast treatment.

As for the onions, it is interesting to note that a significant difference was only detected in Season 3, which was the driest and potentially the most stressful season for the crops. The maize crop was irrigated in January 2025 and not in previous seasons. Vermicast is recognised to benefit plants under stresses such as drought conditions e.g. (Aboelsoud & Ahmed, 2020; Rehman *et al.*, 2023). Whether the vermicast appeared to perform in this season due to plant stress is unknown, but it is a likely possibility, given that the onion crop also showed a beneficial impact of the same vermicast treatment in the same season. This was previously discussed in Section 5.6.3.

5.6.6 Further notes on vermicast and crop production

The chicken litter and vermicast treatments provided additional nutrients to the crops as it was not practical to alter fertiliser applications in a commercial setting. It would also have been difficult to balance nutrient supply between the chicken litter and vermicast and also between seasons. Nutrient supply from commercial and organic fertilisers are dissimilar, however, they can result in similar nutrient uptake by plants (Lin *et al.*, 2022). The addition of nutrients may explain part of the beneficial impacts of vermicast on the onion crop in Season 3. However, the commercial crops were grown under fertiliser plans optimised by the growers, based on soil testing and crop knowledge. No testing of crop leaves were done to check plant nutrient uptake. However. it is unlikely that the onions were under fertilised, as a significant effect would have also been expected in the 12.5 t FM/ha vermicast treatment in Season 3, if this were the case. The lack of a significant difference for the 12.5 t FM/ha vermicast treatment was not due to low power. Relatively large quantities of nutrients were applied in vermicast (as they were in chicken litter). However, there was little evidence that cumulative treatment applications affected soil parameters (C%, Olsen P, N%, pH and C:N) analysed between trial initiation and final harvest in Trial B, three years later. Differences were more likely to have been due to applications made in Season 3, than a cumulative effect of annual application. Regardless, if the benefit of the vermicast application was primarily due to nutrient supply, the cost benefit and sensitivity analyses have demonstrated that the addition of vermicast provided a financial net benefit. If nutrients were supplied in excess, there are opportunities to save fertiliser costs through substitution or supplementation using vermicast.

The lack of significant differences in Season 1 may be explained by small effect size, delayed application and/or adverse weather conditions in late. Except for the reduction in onion density in the chicken litter treatment, the lack of significant differences in Season 2 may be explained by low power as there was a large effect size detected. However, given the results of the Chapter 3 vermicomposting trials and discussion in Section 5.6.6.1, it is reasonable to hypothesise that although an effect was found in Season 3, the age of the vermicast used for these field trials may have affected its overall potential impact over the three seasons.

5.6.6.1 Vermicast age

The precise age of the vermicast used in the trials was unknown, however it was estimated to have been at least two years old by the time the trials began in 2022 (Season 1). By the time it was applied in Season 3, it would have been at least 5 years old.

A study by Harit *et al.* (2014) measured the effects of storage on vermicast produced from neem leaves. Significant physical and chemical changes were observed after different periods of storage, ranging from <7 to >120 days. The vermicomposting period was very short (two weeks) so it is not clear that pure vermicast was produced, rather than a vermicompost. The authors did not state the number of replicates used, however the results showed that there was a significant difference in all physical properties measured as well as EC, organic C, total N and element contents. Changes were attributed to ongoing microbial activity in storage. However, the changes in chemical properties were unrealistic e.g. total P decreased although the material was stored in plastic bags. Phosphorus does not volatilise and microbial uptake would not affect total P. There were issues with other nutrients too so chemical analyses from this paper are henceforth ignored. Bulk density increased during storage while moisture content and water holding capacity decreased. Vermicasts stored for 90 and >120 days were noted to have developed a degree of water repellency (hydrophobicity). Although not observed in the vermicast used in any field, glasshouse or vermicomposting trials reported in this thesis, this has been previously noted as a characteristic of dried/older vermicasts. In their study, the authors suggested this may have been caused by conformational rearrangements (changes in the structure of molecules) in organic matter and excessive dryness.

A study by Scullion *et al.* (2003) showed that microbial communities in vermicast produced by *Lumbricus terrestris* (an anecic species) and *Lumbricus rubellus* (an endogeic species) were initially dominated by bacteria, and eventually by fungi as the vermicast aged. Based on CO_2 production, microbial activity also slowed over time.

The age of the vermicast used in the field trials may have limited its efficacy as vermicast properties are reported to change in storage. While Season 3 showed a significant benefit of vermicast application, the vermicast was estimated to be at least five years old. The plant growth index trial reported in Section 3.3.3.3 (part of the vermicomposting trials of this thesis) showed that a subsample of the vermicast used in this current trial had much lower vigour than the fresh trial vermicomposts produced when trialled at a 1:1 with sand for tomato plants. Further, no obvious differences were detected in seed germination in trials conducted in Chapter 3 or Chapter 4.

5.6.6.2 Higher incidence of diseases noted in Trial B

It is interesting to note that in each of the three seasons, location Trial B grew crops where the presence of at least one pest or disease was recorded. This was not the case in Trials A or C although this does not mean pests and diseases were not present in these crops. As weather and crop type varied each year, it is not possible to determine whether this location is a hotspot for pest and disease incidence. However, Trial B's local history as the oldest cropping site on the farm (maize, potato and onion rotation since the 1990's) and its poorly drained alluvium subsoil may have contributed to pest and disease pressure in the three crops.

5.7 Conclusions

All trial sites differed in soil type and recent land management. These were noted to affect pH as well as the concentration of Na, P, Mn and Cu between the soils of the three trials. It was not possible to determine whether these factors affected trial outcomes.

As expected, both the chicken litter and vermicast varied within and between seasons. This was due to their organic nature. The vermicast trialled was from old stock which may have reduced its effectiveness impacting the crops trialled. However, there was a significant beneficial effect of the 25 t FM/ha vermicast treatment on both onion density and yield in Trial B, Season 3. When scaled up to a t/ha basis, the 11.6 t/ha onion yield increase between the 25 t FM/ha vermicast treatment and the Control, was estimated to be able to provide an additional profit of $4,194/ha. This held up under all sensitivity scenarios, except where yield was reduced to 5.2 t onions/ha and profit was reduced by 50%. Conversely, there was a detrimental effect of chicken litter on onion density in Seasons 2 and 3. In Season 3, this resulted in a heavier average onion mass, but did not translate to an increase in yield. Increases in Season 3 average onion mass under the chicken litter treatment were attributed to reduced competition for resources

There did not appear to be an effect of treatment on onion quality (disease prevalence in Season 3). Disease pressure (*Fusarium oxysporum*, and potentially *Pectobacterium carotovorum)*, crop management, trial location and/or dry weather conditions may have contributed to reduced onion yields across all treatments in Season 3. The actual cause of the reduction in Season 3 onion yield is unknown, though it appears low rainfall increased disease pressure contributed.

There was no treatment effect detected in the potato crops for yield or quality data. A column effect was detected in the count of large tubers and specific gravity, but this was accounted for in the trial design and had no effect on treatment outcomes. Low power

was found for yield and quality tests, indicating treatment differences may have gone undetected. The low power issue was compounded in Seasons 1 and 3 where Column D was removed from the analysis due to incomplete data.

The 25 t FM/ha vermicast treatment produced greater maize kernel mass than the Control and 12.5 t FM/ha vermicast treatments in Season 3. Maize grain quality varied between Seasons 2 and 3, and this may be due to the maturity stage at which the samples were collected. Maize in Season 2 was destined for grain and was thus more mature (older and drier) than Season 3 maize, which was destined for silage.

The significant differences in the 25 t FM/ha vermicast treatment were only observed in Season 3, for both maize and onions. As the trials for the previous seasons were underpowered, significant differences may have been missed due to Type II error (false negatives) and/or the differences may have become apparent due to the dry growing season i.e. the vermicast may have performed noticeably better when plants were under stress.

Vermicast age was considered as a factor that may have limited observed responses. The fact that a significant difference was detected in the Season 3 onions when the vermicast was about five years old indicates that the vermicast still retained some vigour and/or a cumulative effect e.g. of nutrient supply was detected after three years off application. Other explanations for significant yield differences only being detected in Season 3 onions are statistical power, effect sizes and the possibility that the vermicast performs under stressful conditions (overall treatment and Control yields were reduced in Season 3).

Soil C% increased significantly between Season 1 and Season 3 in Trial B, with a near-significant interaction between season and treatment suggesting the increase was driven primarily by the 25 t FM/ha vermicast treatment. There was not enough evidence to suggest this was a direct treatment effect as the baseline sample was taken prior to treatment application in Season 1 and the final sample taken post-harvest. The vermicast and chicken litter treatments applied C to the soil and the results likely reflect the direct addition of C, rather than a treatment effect resulting in soil C sequestration through crop growth. Olsen P also increased significantly over the trial period, but this was across all treatments, including the Control and therefore may have been a result of fertiliser applied to the crop.

Environmental factors such as weather varied between seasons and likely had an effect on onion production, though it was not possible to determine this for potatoes as variables such as crop and number of replicates changed between the seasons for this crop,

or for maize as the crops were destined for different purposes between seasons. Trial B was noted to grow crops where pests and diseases were detected in each Season. These were root knot nematode (unconfirmed identification) in Season 1 potatoes, aphids in Season 2 maize, and *Fusarium oxysporum* and *Pectobacterium carotovorum* in Season 3 onions. This may not have been influenced by trial location and/or soil type/history, though seasonal weather patterns can also influence pest and disease pressure.

Chapter 6
Conclusions and future work

6.1 Conclusions

This thesis explored the idea of reusing specific organic resources (chicken processing dissolved air flotation (DAF) sludge and cardboard) as feedstocks for *Eisenia fetida* whose vermicast could then be used as a soil conditioner to enhance existing food production. This section summarises the overall conclusions of this body of work and provides recommendations future work in the study area.

The hypotheses explored in this research include:

i. Vermicast can be successfully produced from chicken poultry DAF blended with cardboard.
ii. Vermicast application timing impacts crop yield.
iii. Vermicast application is beneficial for crop yield on soils with low Olsen P.
iv. Vermicast application to soils improves crop yield and quality (more so than chicken litter) on a commercial market garden.

This thesis is relevant to the horticultural industry's Aotearoa Horticulture Action Plan, as it investigates the potential for alternative nutrient sources which could reduce the horticulture sector's reliance on imported fertilisers such as phosphorus, offsetting production costs, increasing production security and farmgate value. Integrating this work to fit into a circular economy model would involve scaling up the quantity of vermicompost/vermicast produced and trialling it on commercial crops, investigating the potential for supplementation of rock phosphate fertiliser derivatives. The results of this research also support industry resilience to climate change where longer drought periods are expected.

6.1.1 Contributions to science

This research has made multiple contributions to the vermicomposting and vermicast application research spaces. For the first time cardboard and chicken processing DAF sludge have been used to produce vermicomposts that meet the New Zealand Standards for Composts, soil conditioners and mulches (NZS 4454:2005) and provide a benefit to plant growth and potentially seedling emergence.

For the first time a detailed study on the effects of vermicast and crop rotation of maize, onion and potatoes has been conducted in New Zealand. The field trials showed that kernel mass in maize was increased under the 25 t FM/ha treatment relative to the Control in the third season. The 25 t FM/ha treatment also showed an increase in onion density and yield relative to the Control. When the yield increase was used in a cost-benefit analysis, this vermicast application rate was shown to have a positive financial benefit for growers (>$800/ha) even with the costs associated with vermicast included. Even though increasing vermicompost age has been previously shown to reduce the beneficial properties of vermicompost, this study found a beneficial effect on yield and density of onions, and kernel mass for maize in the third season of the trial. Application of this commercially produced vermicast was found to be a good supplement for DAP fertiliser for onions grown on low Olsen-P soil.

6.1.2 Vermicomposting experiments

Chicken processing DAF sludge can be vermicomposted with cardboard to produce vermicompost compliant with the NZS 4454:2005 New Zealand Standards for composts, soil conditioners and mulches. The vermicomposting experiments were run at lab scale (up to 2.5 kg dry matter (DM) feedstock). Trialled feedstocks were 2:1, 3:1 and 4:1 mixes of cardboard to DAF on a DM basis. Except for plastic contamination and one final pH measurement, all conditions under NZS 4454:2005 were met by the feedstocks trialled. The plastic contamination can be overcome by changing the source of the cardboard. This was demonstrated in the pilot trial where a different source of cardboard was used successfully, and no plastic contamination was observed. Cadmium (Cd) contamination was a potential concern in the pilot trial as both the DAF sludge and the cardboard appeared to have excessive amounts (compared against the Guidelines for the safe application of biosolids to land in New Zealand). However, these results were reported below quantitation limits (QL) so Cd contamination may not have been an issue. Using a different source of cardboard in the main trial appeared to remove the potential issue of Cd as it was found below the guideline limits, however again Cd levels were detected below QL.

An industrially produced “White Gold vermicast”, was also trialled against NZS 4454:2005 and shown to be a vermicompost. This vermicompost was the same as the vermicast used in Chapters 4 and 5, though it is still referred to as a vermicast in these Chapters as this was what the product was marketed as.

Chapter 3 demonstrated the trial vermicomposts derived from DAF and cardboard had a beneficial effect on both radish seed germination and tomato growth. Interestingly, while the White Gold vermicompost had a beneficial effect on radish seed germination (and although not statistically significant, also improved total onion emergence and rate of emergence in Chapter 4), its benefits to tomato plants were limited and well below that of the trial vermicomposts. The difference in performance was likely affected by feedstock inputs, method of vermicompost production (outdoor windrows vs controlled laboratory conditions) and age of vermicompost.

Chapter 3 also demonstrated that overwatered vermicomposting feedstocks can be recovered and vermicomposts compliant with NZS 4454:2005 that are beneficial to plant growth can still be produced.

6.1.3 Plant production experiments

6.1.3.1 Glasshouse trials

The glasshouse trials showed that vermicast applied at a rate of 12.5 t fresh matter (FM)/ha/year to pelletised onion seeds increased the rate of emergence and total number of emerged seedlings, especially when broadcast rather than incorporated into the soil. These trials were underpowered, which increased the risk of Type II errors (false negatives). Although not statistically significant, the same trend was observed in two trials performed a year apart on different soils. The combination of low power and the same trends observed in both trials indicate the effect of vermicast on seedling emergence warrants further investigation.

The timing of vermicast applied at 12.5 t FM/ha did not appear to have an effect on onion size or mass in either of the glasshouse timing trials. In the first glasshouse trial (Trial 1), onions were grown on a Typic Orthic Allophanic soil obtained from the Matamata field trial site (Trial C). These onions were smaller and lighter than those grown in the field trial in the same season. The glasshouse onions were sown 18 days later than the field trials, but the difference in size and mass between the concurrent trials can be attributed to environmental conditions (the glasshouse trial often exceeded optimal temperatures for onion bulb development). In the subsequent glasshouse trials (Trials 2 and 3), onion bulb mass was about twice that of Trial 1. The differences between Trial 1 and Trials 2 and 3 can be attributed to soil and environmental conditions (cooler temperatures during bulb development). All soils used in the glasshouse trials were Typic Orthic Allophanic soils, however location and land management differed. The soil from Trial 1 was from Matamata and has been under cropping management for decades, though

it has only been under maize, potato onion crops since 2017. The soil from Trials 2 and 3 was from under pasture in Ohakune. This site did not have a cropping history and was selected for its low Olsen P content.

There was no effect of reduced P application to onion size, mass or root DM production under glasshouse conditions either with or without vermicast applied at 12.5 t FM/ha.

Regarding direct measurements on onions, all three glasshouse trials were underpowered, so there was a relatively high risk of detecting false negative results. For harvest data, Trial 1 had four replicates per treatment. This trial was shown to be underpowered for harvest measurements of onion mass, size and root DM production. As high temperatures affected onion growth, the trial was repeated the following year, but on a different soil type. As environmental conditions had been found to affect the trial results, it was concluded that treatment differences would be more obvious under mor favourable conditions therefore the trial design could be replicated the following year. While Trial 2 and 3 were intended to have a minimum of four replicates, limited resources resulted in only three replicates per treatment. Although conditions were more favourable (cooler), resulting in onions about twice as heavy as Trial 1, treatment variation was low, and these trials also ended up being underpowered. Post-hoc analysis showed that four replicates would not have been enough to detect differences anyway.

Onion root DM production appeared to be limited by soil volume/pot size as there were no significant differences in total root DM production between Trial 1 and Trial 2. This was despite Trial 2 producing almost twice the yield of Trial 1 and significantly more medium sized (60-80 mm) onion bulbs.

Although there were no differences detected in onion mass, size or root DM production for Trial 3, final soil Olsen P under VP75 (vermicast at 12.5 t FM/ha with 75% recommended diammonium phosphate (DAP) fertiliser) was not significantly different to the Control (P100; 100% recommended DAP fertiliser), suggesting that vermicast may supplement DAP fertiliser by up to 25% on low Olsen P soil without reducing soil P availability. As the onion measurements were underpowered, any agronomic benefits associated with maintained soil P availability under VP75 may not have been detected. This also includes detrimental effects of onions grown under suboptimal P fertiliser application rates.

6.1.3.2 Field trials

Effects were detected even with underpowered trials under field conditions. The field trials on the three commercial crops had either neutral or beneficial effects. Low power was a common theme in these trials, even when effect sizes were large e.g. Season 2 onion trial. The 25 t FM/ha vermicast rate clearly benefited onions in the third/final season, when overall yield in all treatments, including the Control (normal farm management) was depressed compared to yields anticipated by the growers. This was calculated to provide a $812/ha net benefit. The same treatment also increased the kernel mass of maize grown for silage compared to the Control.

Season 1 was the wettest, partially due to an unseasonal amount of rain (>300 mm) in January, though it tended to have more rainfall per month than Seasons 2 and 3. Season 1 had 713 mm more rainfall than the 20-year average, while Seasons 2 and 3 had 87 and 150 mm less. Weather conditions were driest in Season 3 for an extended period over November to March (most of the crop growth and development period). All seasons were 0.6-1.4°C warmer than the 20-year average.

Trial location, soil type, recent management and/or weather conditions are factors that may have influenced treatment performance over the experimental period. These factors are not suggested to have directly caused any specific outcomes. Season 3 was the driest growing season and this correlated with significant differences being detected in onion density and yield, and maize kernel mass for the 25 t FM/ha treatments. Although successive annual applications of vermicast may have increased soil fertility and contributed to crop performance, fertiliser value was unlikely to be the reason for the beneficial effect of vermicast.

In the onion trials, chicken litter had a detrimental effect on onion density in Seasons 2 and 3. In Season 3, this resulted in an increase in average onion mass, however, overall yields were reduced, especially compared to the 25 t FM/ha vermicast treatment. No beneficial effects of chicken litter were observed in any trials.

6.2 Future work

6.2.1 Upscaling vermicomposting of DAF sludge and cardboard

It was not possible to produce vermicast for the glasshouse and field trials as part of this research, as not enough was known about the suitability of cardboard and DAF sludge for vermicomposting together. Instead, laboratory scale pilot trials were conducted. The vermicomposting trials demonstrated that NZS 4454:2005 compliant vermicomposts can be produced from cardboard/DAF sludge feedstocks at lab scale under laboratory

conditions. The recommended next step for this research is to determine the feasibility of upscaling management of these organic wastes, with the aim to produce vermicast for commercial use. Considerations include:

- paper waste selection – plastic, heavy metal and per- and polyfluoroalkyl substances (PFAS) contamination and heavy metal supply, landfill diversion, moisture-holding capacity,
- DAF sludge – heavy metal supply, odour management, pest (fly) control,
- pathogen control – source clean inputs,
- vermicomposting system – contained facility, outdoors, space and resources required, weed management,
- moisture control – irrigation, drainage/leachate,
- vermicomposting operation location – proximity to waste, transport costs, customers,
- application at scale – suitable machinery, recommended application rates,
- market for vermicast/vermicompost use, potential for P fertiliser supplementation, pest and disease management,
- cost-benefit analyses – potential for worm biomass to be used as a protein supply for other industries,
- length of time to produce vermicast/vermicompost, and
- storage of vermicast/vermicompost – effect of age on plant growth.

While there would be a trade-off regarding time taken to finish vermicomposting a feedstock, converting all feedstock to vermicast would produce a higher-quality soil conditioner than vermicompost. The volume reduction would also be greater, with nutrients concentrating further in the final product reducing transport costs and application rates. The finer vermicast product would likely be suitable for conventional fertiliser spreaders, unlike vermicompost which would require a muck spreader for land application at scale.

6.2.2 Further investigation into application method and P cycling

As the timing and P supplementation glasshouse trials were underpowered and used an older vermicast, there are opportunities for further learning in these areas. Trials with more replicates and fresher vermicast could be used. For onion crops, other areas to explore include root production, leachate mitigation, soil type, rate of vermicast application and vermicomposting inputs. Investigations into P cycling in soils receiving vermicast could be designed to investigate the influence of Olsen P on P cycling. Was the nature of the final Olsen P results due to chemical or biological factors, a combination of both, or something else e.g. the direct addition of P from the vermicast?

While there are advantages in controlling environmental factors, it is well known that field trials often perform differently to glasshouse trials, however it is performance in the field that matters. Low power was an issue in some of the trials – Season 1 and 2 of the onion trials, Season 2 and 3 of the maize and all seasons of the potato trials were

underpowered. The effect size in Season 1 was small so differences between treatments would have been minor if a significant difference had been found. This was partially attributed to the late application of treatments (almost two months post-sowing). While the effect size in Season 2 was large, significant differences were not detected, except where chicken litter reduced onion density. Given the large effect size and low power, it is possible that treatment effects went undetected. The vermicast trialled in Season 3 of the field trials showed benefits for onions in a stressful season (yields were lower than the previous two season). Yields of all treatments were depressed, however the 25 t FM/ha vermicast treatment produced a significantly higher yield than the other treatments – enough to make a measurable financial benefit. If it is possible to partially offset the application of mined/imported fertilisers e.g. P and still achieve a yield increase this could add a layer of security for growers. Volatility in fuel and fertiliser prices and the potential for interruptions to New Zealand's rock phosphate imports highlight the importance of this research. Field trials on soils with a range of Olsen P soils could further explore the potential for vermicast to supplement rock phosphate and its derivative fertilisers.

Chapter 7

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Chapter 8

Appendices

8.1 Appendix 1: main vermicomposting trial raw data

Table 8-1: pH and EC (electrical conductivity) raw data. DAF = dissolved air flotation sludge from chicken processing.

Treatment	EC (dS/m)	pH
DAF	3.624	5.89
4B 2:1 Cardboard:DAF	2.24	5.8
5B 3:1 Cardboard:DAF	1.498	5.79
6B 4:1 Cardboard:DAF	1.272	5.81
Cardboard	0.547	7.53

Table 8-2: raw worm biomass data. DAF = dissolved air flotation sludge from chicken processing.

Treatment	Worm biomass (g)
1A 2:1 Cardboard:DAF	82.56
2A 3:1 Cardboard:DAF	87.52
3A 4:1 Cardboard:DAF	37.4
4B 2:1 Cardboard:DAF	79.25
5B 3:1 Cardboard:DAF	52.52
6B 4:1 Cardboard:DAF	64.68

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Table 8-3: raw data (toxicity trial average root length (up to 10 seedlings per unit)). FM = fresh matter. DAF = dissolved air flotation sludge from chicken processing.

Vermicompost application method	Treatment	Average root length (mm)
Incorporated (12.5 t FM/ha)	1A 2:1 Cardboard:DAF	31
	2A 3:1 Cardboard:DAF	34
	3A 4:1 Cardboard:DAF	46
	4B 2:1 Cardboard:DAF	24
	5B 3:1 Cardboard:DAF	32
	6B 4:1 Cardboard:DAF	34
	White Gold	27
Broadcast (12.5 t FM/ha)	1A 2:1 Cardboard:DAF	37
	2A 3:1 Cardboard:DAF	47
	3A 4:1 Cardboard:DAF	41
	4B 2:1 Cardboard:DAF	42
	5B 3:1 Cardboard:DAF	42
	6B 4:1 Cardboard:DAF	43
	White Gold	37
Pure	1A 2:1 Cardboard:DAF	96
	2A 3:1 Cardboard:DAF	86
	3A 4:1 Cardboard:DAF	92
	4B 2:1 Cardboard:DAF	99
	5B 3:1 Cardboard:DAF	91
	6B 4:1 Cardboard:DAF	80
	White Gold	102
Control	Dalton Sand	18

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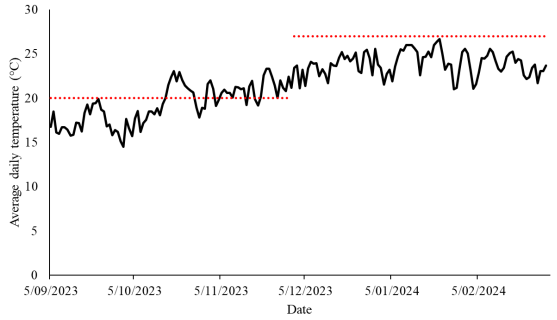
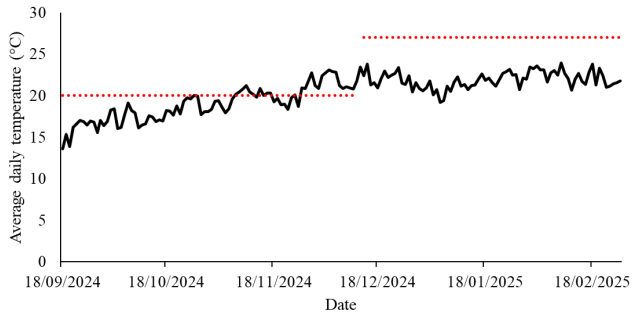
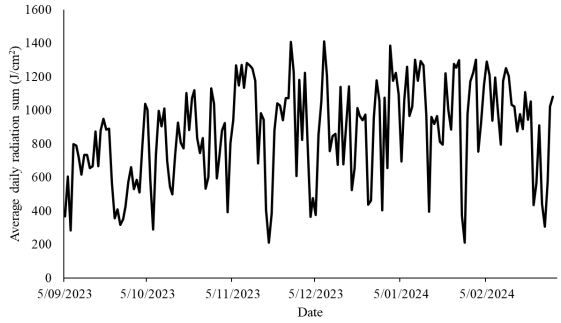
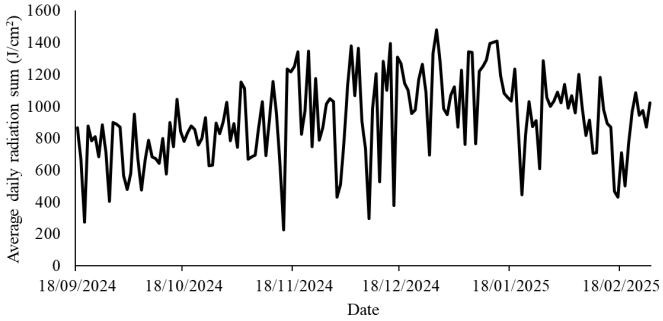
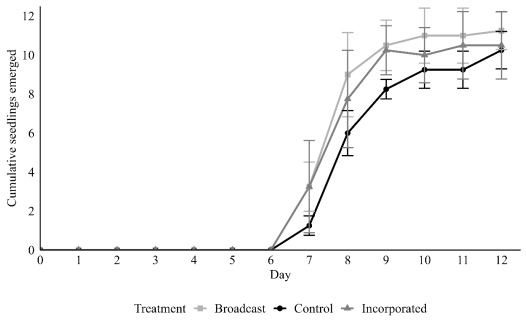
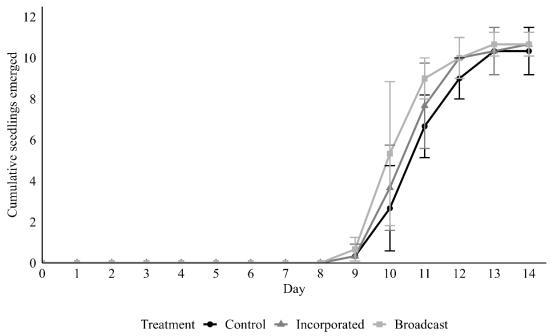
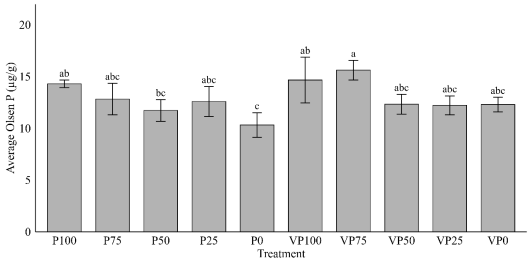
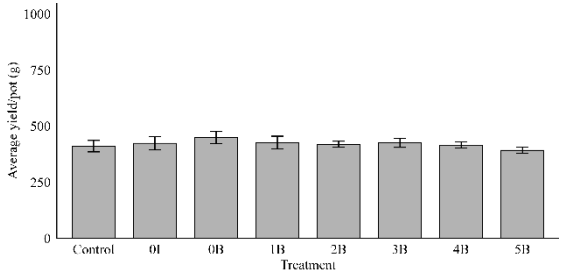
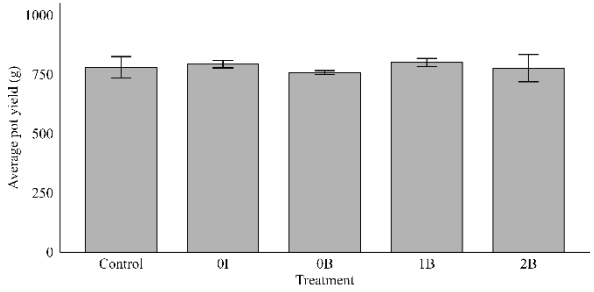
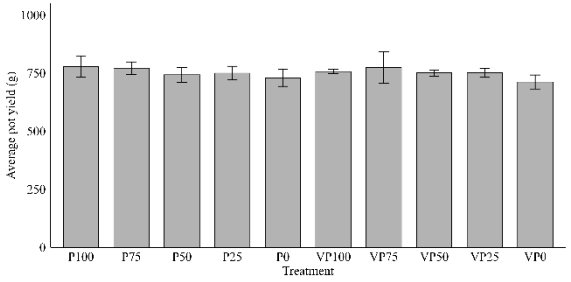
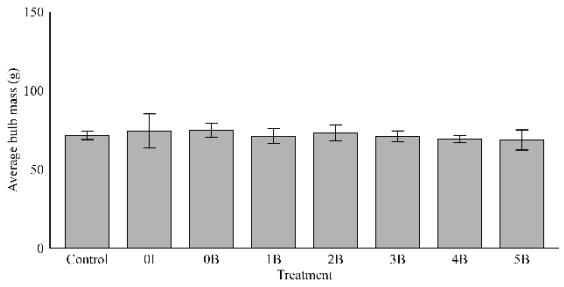
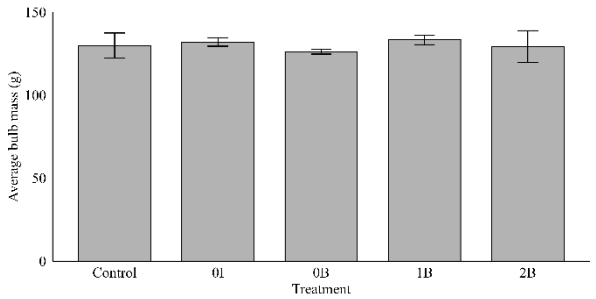
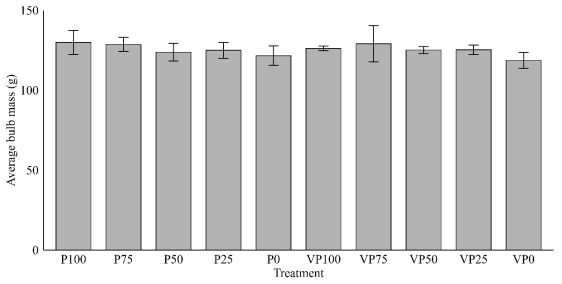
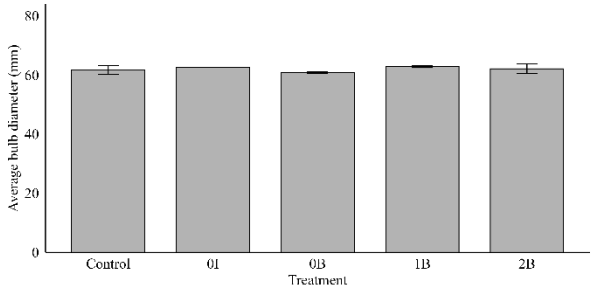
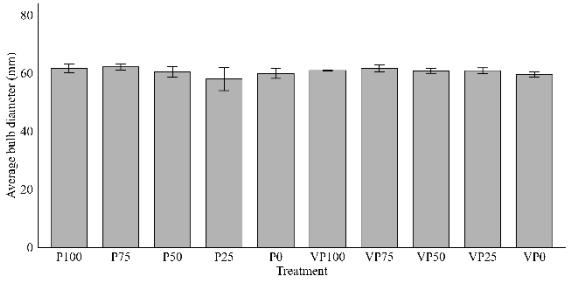
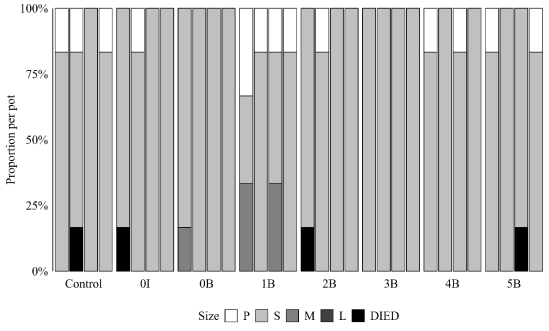
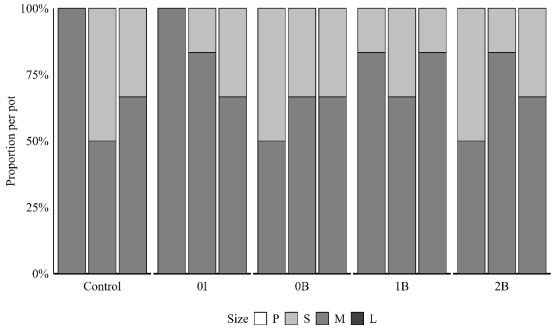
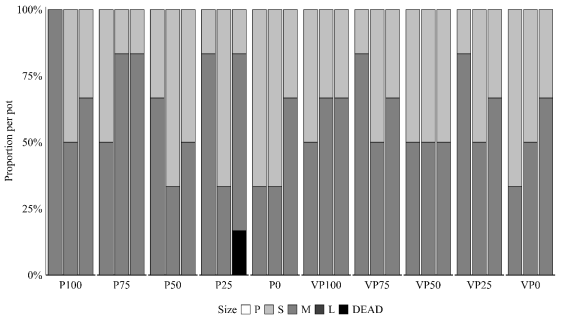
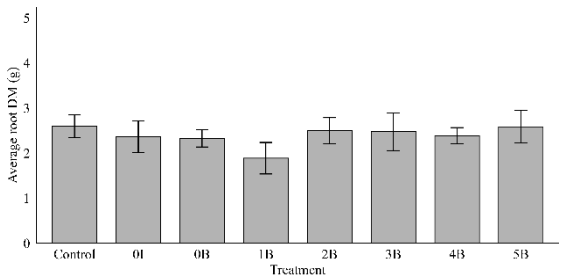
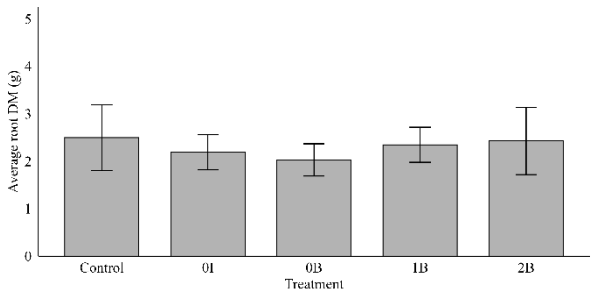
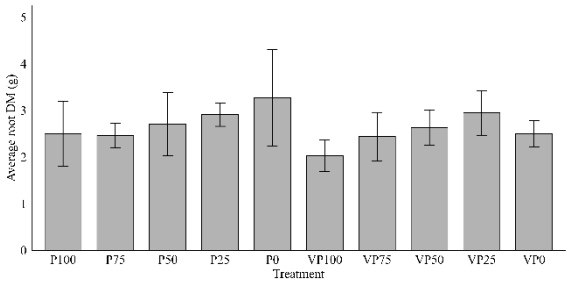
8.2 Appendix 2: glasshouse trial comparisons for onions

	Trial 1: vermicast application timing	Trial 2: vermicast application timing	Trial 3: P supplementation
Average temperature			
Average radiation			

	Trial 1: vermicast application timing	Trial 2: vermicast application timing	Trial 3: P supplementation
Seedling emergence			
Olsen P			
Yield			

	Trial 1: vermicast application timing	Trial 2: vermicast application timing	Trial 3: P supplementation
Bulb mass			
Bulb diameter			
Bulb size proportion			

	Trial 1: vermicast application timing	Trial 2: vermicast application timing	Trial 3: P supplementation
Root mass			

8.3 Appendix 3: baseline soil analyses

8.3.1 Element analyses

Table 8-4: Trial A average element concentration by column. ANOVA = analysis of variance.

	Column average concentration (mg/kg dry soil)				p value		Tukey's Honest Significant Difference p value					
Element	**A**	**B**	**C**	**D**	**ANOVA**	**Levene's test**	**B vs A**	**C vs A**	**D vs A**	**C vs B**	**D vs B**	**D vs C**
Na	3.47	2.64	2.19	2.36	1.00E-03	0.41	0.03	1.00E-03	3.00E-03	0.30	0.65	0.91
Mg	4.83	6.04	4.74	3.53	0.04	0.08	0.39	1.00	0.34	0.34	0.02	0.39
Ca	50.73	44.98	49.87	38.83	0.25	0.08	0.79	1.00	0.27	0.86	0.76	0.33
P	21.44	24.35	25.08	20.10	0.31	0.39	0.75	0.60	0.97	0.99	0.48	0.35
Mn	6.54	8.95	7.13	4.10	0.04	0.00	0.39	0.98	0.38	0.61	0.03	0.22
Fe	92.07	83.70	79.55	86.23	0.42	0.00	0.67	0.36	0.86	0.94	0.99	0.80
Cu	0.08	0.09	0.08	0.07	0.29	0.34	0.94	1.00	0.52	0.90	0.25	0.59

Table 8-5: Trial A average element concentration by row. ANOVA = analysis of variance.

	Row average concentration (mg/kg dry soil)				p value		Tukey's Honest Significant Difference p value					
Element	**1**	**2**	**3**	**4**	**ANOVA**	**Levene's test**	**2 vs 1**	**3 vs 1**	**4 vs 1**	**3 vs 2**	**4 vs 2**	**4 vs 3**
Na	2.56	2.69	2.65	2.76	0.98	0.39	0.99	1.00	0.97	1.00	1.00	0.99
Mg	4.50	5.22	4.68	4.74	0.91	0.07	0.89	1.00	0.99	0.95	0.96	1.00
Ca	50.94	45.74	41.62	46.11	0.61	0.69	0.87	0.54	0.89	0.93	1.00	0.91
P	23.99	20.94	20.53	25.51	0.29	0.15	0.72	0.63	0.95	1.00	0.42	0.35
Mn	6.69	6.72	6.35	6.96	0.99	0.02	1.00	1.00	1.00	1.00	1.00	0.99
Fe	89.36	91.92	77.47	82.80	0.20	0.00	0.98	0.34	0.77	0.20	0.56	0.86
Cu	0.08	0.10	0.07	0.07	0.13	0.67	0.32	0.96	0.98	0.16	0.18	1.00

Table 8-6: Trial B average element concentration by column. ANOVA = analysis of variance.

	Column average concentration (mg/kg dry soil)				p value		Tukey's Honest Significant Difference p value					
Element	**A**	**B**	**C**	**D**	**ANOVA**	**Levene's test**	**B vs A**	**C vs A**	**D vs A**	**C vs B**	**D vs B**	**D vs C**
Na	2.58	1.92	2.36	1.76	0.21	0.36	0.40	0.95	0.23	0.70	0.98	0.48
Mg	4.06	4.36	3.49	3.98	0.53	0.61	0.95	0.76	1.00	0.46	0.91	0.83
Ca	42.43	53.05	48.25	46.80	0.39	0.04	0.32	0.76	0.88	0.85	0.72	0.99
P	18.78	15.92	20.69	17.74	0.29	0.04	0.63	0.85	0.97	0.24	0.87	0.61
Mn	4.18	1.62	3.13	2.97	0.12	0.00	0.08	0.69	0.60	0.43	0.51	1.00
Fe	85.52	79.13	84.31	85.74	0.93	0.32	0.94	1.00	1.00	0.97	0.93	1.00
Cu	0.06	0.06	0.06	0.07	0.39	0.08	1.00	0.82	0.79	0.76	0.84	0.32

Table 8-7: Trial B average element concentration by row. ANOVA = analysis of variance.

	Row average concentration (mg/kg dry soil)				p value		Tukey's Honest Significant Difference p value					
Element	**1**	**2**	**3**	**4**	**ANOVA**	**Levene's test**	**2 vs 1**	**3 vs 1**	**4 vs 1**	**3 vs 2**	**4 vs 2**	**4 vs 3**
Na	2.13	2.22	2.38	1.90	0.77	0.88	1.00	0.95	0.96	0.99	0.89	0.73
Mg	4.00	3.58	3.99	4.33	0.67	0.41	0.89	1.00	0.95	0.90	0.61	0.94
Ca	51.76	47.07	46.01	45.69	0.76	0.77	0.88	0.80	0.78	1.00	1.00	1.00
P	16.99	15.44	20.95	19.75	0.08	0.05	0.88	0.28	0.57	0.09	0.22	0.94
Mn	2.55	3.18	3.15	3.02	0.95	0.03	0.95	0.96	0.98	1.00	1.00	1.00
Fe	85.31	90.62	82.19	76.59	0.62	0.03	0.96	0.99	0.84	0.86	0.57	0.95
Cu	0.06	0.07	0.06	0.06	0.03	0.46	0.06	0.79	0.96	0.25	0.02	0.51

Table 8-8: Trial C average element concentration by column. ANOVA = analysis of variance.

	Column average concentration (mg/kg dry soil)				p value		Tukey's Honest Significant Difference p value					
Element	**A**	**B**	**C**	**D**	**ANOVA**	**Levene's test**	**B vs A**	**C vs A**	**D vs A**	**C vs B**	**D vs B**	**D vs C**
Na	1.33	2.04	1.73	0.82	0.04	0.12	0.30	0.72	0.55	0.85	0.03	0.13
Mg	3.84	3.98	5.62	5.15	0.00	0.68	0.99	0.01	0.04	0.01	0.07	0.67
Ca	56.38	51.08	39.98	45.59	0.05	0.30	0.75	0.04	0.22	0.20	0.73	0.71
P	16.61	18.28	24.32	24.99	1.40E-04	0.91	0.67	9.70E-04	4.70E-04	0.01	3.00E-03	0.97
Mn	1.66	1.71	9.40	8.98	3.50E-10	0.36	1.00	6.00E-09	1.10E-08	6.40E-09	1.20E-08	0.80
Fe	71.97	79.92	86.77	85.96	0.15	4.20E-04	0.63	0.17	0.20	0.73	0.80	1.00
Cu	0.06	0.07	0.09	0.09	2.80E-06	0.02	0.50	1.90E-05	2.00E-05	1.40E-04	1.40E-04	1.00

Table 8-9: Trial C average element concentration by row. ANOVA = analysis of variance.

	Row average concentration (mg/kg dry soil)				p value		Tukey's Honest Significant Difference p value					
Element	**1**	**2**	**3**	**4**	**ANOVA**	**Levene's test**	**2 vs 1**	**3 vs 1**	**4 vs 1**	**3 vs 2**	**4 vs 2**	**4 vs 3**
Na	1.66	1.21	1.75	1.30	0.64	0.79	0.80	1.00	0.88	0.71	1.00	0.80
Mg	4.77	4.61	4.86	4.35	0.90	0.01	1.00	1.00	0.94	0.99	0.98	0.89
Ca	55.78	47.02	45.69	44.55	0.31	0.01	0.52	0.41	0.32	1.00	0.98	1.00
P	21.68	20.56	21.55	20.40	0.97	0.89	0.99	1.00	0.98	0.99	1.00	0.98
Mn	4.85	5.54	5.76	5.59	0.99	0.00	1.00	0.99	0.99	1.00	1.00	1.00
Fe	76.71	86.41	85.49	76.00	0.35	0.00	0.55	0.62	1.00	1.00	0.49	0.57
Cu	0.08	0.08	0.08	0.08	0.96	0.03	1.00	0.99	0.98	0.98	0.97	1.00

8.3.2 pH analyses

Table 8-10: Tukey's Honest Significant Difference p values for Baseline soil pH data. Non-significant values ($p > 0.05$) indicate homogeneity between trial/row/column pairs.

Test	Comparison	p-value
Trial effect	B-A	1.49E-09
Trial effect	C-A	7.13E-05
Trial effect	C-B	0.007
Trial A columns	B-A	0.162
Trial A columns	C-A	0.077
Trial A columns	D-A	0.678
Trial A columns	C-B	0.968
Trial A columns	D-B	0.024
Trial A columns	D-C	0.011
Trial B rows	2-1	0.507
Trial B rows	3-1	1.46E-05
Trial B rows	4-1	6.05E-05
Trial B rows	3-2	9.74E-05
Trial B rows	4-2	4.86E-04
Trial B rows	4-3	0.704
Trial C columns	B-A	0.333
Trial C columns	C-A	0.46
Trial C columns	D-A	0.947
Trial C columns	C-B	0.029
Trial C columns	D-B	0.622
Trial C columns	D-C	0.222

8.4 Appendix 3: additional statistical test results

Table 8-11: P-values for Shapiro-Wilk tests for normalcy in onions.

Treatment	Density (onions/m^2)	Individual onion mass (g/onion)	Yield (kg/m^2)
Season 1, Trial A			
Control	0.874	0.765	0.586
Chicken litter	0.629	0.901	0.256
12.5 t/ha Vermicast	0.145	0.372	0.949
25 t/ha Vermicast	0.363	0.585	0.121
Season 2, Trial C			
Control	0.378	0.074	0.664
Chicken litter	0.046	0.729	0.027
12.5 t/ha Vermicast	0.867	0.632	0.498
25 t/ha Vermicast	0.828	0.447	0.181
Season 3, Trial B			
Control	0.991	0.227	0.812
Chicken litter	0.136	0.204	0.597
12.5 t/ha Vermicast	0.498	0.699	0.573
25 t/ha Vermicast	0.160	0.986	0.238

Table 8-12: P-values for Shapiro-Wilk tests for normalcy in potatoes.

Treatment	Density (potatoes/m^2)	Individual potato mass (g/tuber)	Yield (kg/m^2)
Season 1, Trial B			
Control	0.900	0.394	0.545
Chicken litter	0.948	0.717	0.335
12.5 t/ha Vermicast	0.780	0.834	0.964
25 t/ha Vermicast	1.000	0.162	0.051
Season 2, Trial A			
Control	0.055	0.728	0.398
Chicken litter	0.377	0.106	0.906
12.5 t/ha Vermicast	0.172	0.858	0.536
25 t/ha Vermicast	0.345	0.261	0.333
Season 3, Trial C			
Control	0.537	0.231	0.367
Chicken litter	0.765	0.803	0.507
12.5 t/ha Vermicast	0.523	0.053	0.188
25 t/ha Vermicast	1.000	0.839	0.907

Table 8-13: P-values for Shapiro-Wilk tests for normalcy in specific gravity of fresh and whiteness values of fried potatoes in Season 3.

Treatment	Specific gravity	Whiteness
Control	0.579	0.426
Chicken litter	0.785	0.046*
12.5 t/ha Vermicast	0.805	0.854
25 t/ha Vermicast	0.774	0.589

Table 8-14: P-values for Shapiro-Wilk tests for normalcy in maize. *Indicates non-normality ($p < 0.05$).

Treatment	Plant density (count/10 m)	Cob mass (kg/100 cobs)	Kernel mass (g DM_{60}/100 kernels)
Season 1, Trial C			
Control	NA	NA	NA
Chicken litter	NA	NA	NA
12.5 t/ha Vermicast	NA	NA	NA
25 t/ha Vermicast	NA	NA	NA
Season 2, Trial B			
Control	0.031*	0.922	0.993
Chicken litter	0.239	0.966	0.502
12.5 t/ha Vermicast	0.332	0.516	0.276
25 t/ha Vermicast	0.378	0.392	0.283
Season 3, Trial A			
Control	0.470	NA	0.339
Chicken litter	0.374	NA	0.256
12.5 t/ha Vermicast	0.430	NA	0.358
25 t/ha Vermicast	0.883	NA	0.337

8.5 Appendix 4: Season 3 onion cost-benefit analyses

Table 8-15: Yield calculations and cost-benefit analysis for Season 3 based on significant yield increase at 25 t FM/ha vermicast application.

		Value	Unit
Yield over sample area (1 m wide)			
	Control	8.5	kg onions/m2
	25 t FM/ha vermicast	10.1	kg onions/m2
Yield over total area of bed (1.375 m wide)			
	Control	4.9	kg onions/m2
	25 t FM/ha vermicast	5.8	kg onions/m2
Yield per ha			
	Control	48.6	t onions/ha
	25 t FM/ha vermicast	57.7	t onions/ha
	Vermicast yield increase	9.1	t onions/ha
Cost-benefit analysis			
	Vermicast cost	$29.95	/t vermicast
	Transport cost	$23.00	/t vermicast
	Spreading cost	$6.00	/t vermicast
	Application rate	25	t vermicast/ha
	Cost of vermicast application	$1,473.75	/ha
	Farmgate profit	$250	/t onions
	Benefit of vermicast application	$2,285.71	/ha
	Total value of vermicast application	$811.96	/ha

Table 8-16: Yield calculations and cost-benefit analysis for Season 3 based on a minimum yield increase (6.7 t onions/ha) to achieve $200 profit at 25 t FM/ha vermicast application.

		Cost sensitivity		Profit sensitivity		Worst case	
Variable	**Base**	**20% increase**	**50% increase**	**20% decrease**	**50% decrease**	**± 20%**	**± 50%**
Vermicast cost $/t vermicast	30	36	45	30	30	36	45
Transport cost $/t vermicast	23	28	35	23	23	28	35
Spreading cost $/t vermicast	6	7	9	6	6	7	9
Cost of vermicast application $/ha	1,474	1,769	2,211	1,474	1,474	1,769	2,211
Farmgate profit $/t onions	250	250	250	200	125	200	125
Benefit of vermicast application $/ha	1,674	1,674	1,674	1,339	837	1,339	837
Total value of vermicast application $/ha	200	-95	-537	-135	-637	-430	-1,374
Total profit for 50 ha crop	10,000	-4,737	-26,844	-6,738	-31,844	-21,475	-68,688

8.6 Appendix 5: weather data

Table 8-17: Weather data for the three Seasons of the field trials. Data provided by MetWatch (https://www.hortplus.com/). ET = evapotrianspiration.

Season	Year	Month	Highest max temp (°C)	Avg temp (°C)	Lowest min temp (°C)	Total rainfall (mm)	Total ET (mm)	Total solar energy (Mj/m²)	Total wind run (km)
1	2022	July	19.1	10.8	-0.1	229.2	37.0	183.9	1684.4
1	2022	August	19.2	10.7	-1.4	106.8	53.6	275.0	1426.3
1	2022	September	20.5	11.8	-0.8	204.2	66.6	335.1	1337.7
1	2022	October	22.9	14.0	-1.7	141.0	94.6	470.5	1438.2
1	2022	November	24.6	16.6	7.7	200.2	108.9	512.6	1439.6
1	2022	December	28.1	19.0	8.4	128.2	141.1	644.9	1169.8
1	2023	January	28.6	19.7	11.3	312.8	124.4	549.6	1754.1
1	2023	February	27.4	19.1	10.1	145.2	110.6	489.8	1364.4
1	2023	March	26.9	16.4	1.6	119.2	108.5	515.8	1028.7
1	2023	April	23.8	15.8	0.9	54.8	66.8	302.9	1618.6
1	2023	May	22.9	13.6	1.4	223.2	43.5	213.2	1755.9
1	2023	June	17.7	10.2	-2.0	139.4	34.6	168.1	1398.3
2	2023	July	16.1	9.5	-1.9	57.4	41.3	196.0	1591.7
2	2023	August	16.7	7.8	-2.3	99.2	57.1	324.6	1031.6
2	2023	September	21.4	12.7	1.2	136.2	74.6	375.6	1962.9
2	2023	October	23.7	14.2	0.3	105.4	100.2	489.7	1820.3
2	2023	November	24.9	15.7	5.2	131.0	109.6	536.9	1375.2
2	2023	December	27.5	19.0	8.5	83.2	116.1	531.3	1301.7
2	2024	January	29.7	20.6	8.8	118.2	156.7	681.8	877.6
2	2024	February	28.6	18.8	7.4	67.8	126.7	562.0	735.1
2	2024	March	25.3	15.1	1.3	117.0	96.1	458.6	873.2
2	2024	April	23.3	14.4	0.9	51.2	66.7	323.0	1009.9
2	2024	May	20.6	10.2	-2.6	121.6	52.8	271.5	963.9
2	2024	June	18.6	10.5	0.9	116.2	36.3	182.6	1130.9
3	2024	July	16.6	8.9	-2.5	94.6	35.3	194.8	932.2
3	2024	August	18.3	9.6	-2.3	95.4	50.1	271.9	1417.2
3	2024	September	20.2	11.3	-0.4	69.4	71.6	369.9	1542.2
3	2024	October	22.0	13.9	3.4	126.8	103.4	524.3	1615.4
3	2024	November	24.7	16.2	4.3	51.6	119.3	576.4	1347.4
3	2024	December	28.3	18.7	6.5	66.8	146.4	669.3	1183.8
3	2025	January	28.4	18.2	5.1	33.2	157.8	712.0	1365.3
3	2025	February	30.2	20.2	7.4	20.8	130.1	548.6	917.0
3	2025	March	27.4	17.1	3.1	29.8	109.2	469.0	1031.7
3	2025	April	23.8	17.1	3.6	225.6	70.8	290.7	1634.6
3	2025	May	19.7	11.9	-0.7	158.8	54.8	262.2	812.5
3	2025	June	19.9	10.4	-1.1	168.2	39.2	187.9	1163.0

8.7 Appendix 6: L*a*b* to RGB conversion

The following code was produced by ChatGPT and used in using RStudio 2025.05.1 Build 513 to convert raw data collected using illuminant C (L*a*b* values) from a Konica Minolta CR-410 chromameter to RGB values.

```
# ----------- Step 1: Lab to RGB (Illuminant C) -----------
lab_to_rgb_C <- function(L, a, b) {
  # Illuminant C white point
  Xn <- 98.074
  Yn <- 100
  Zn <- 118.232

  # Lab → XYZ
  fy <- (L + 16) / 116
  fx <- fy + a / 500
  fz <- fy - b / 200

  f_inv <- function(t) {
    ifelse(t^3 > 0.008856, t^3, (t - 16/116) / 7.787)
  }

  X <- Xn * f_inv(fx)
  Y <- Yn * f_inv(fy)
  Z <- Zn * f_inv(fz)

  # XYZ → linear RGB (sRGB matrix)
  X <- X / 100
  Y <- Y / 100
  Z <- Z / 100

  R_lin <-  3.2406*X - 1.5372*Y - 0.4986*Z
  G_lin <- -0.9689*X + 1.8758*Y + 0.0415*Z
  B_lin <-  0.0557*X - 0.2040*Y + 1.0570*Z

  # Gamma correction
  gamma_correct <- function(u) {
    ifelse(u <= 0.0031308, 12.92 * u, 1.055 * (u)^(1/2.4) - 0.055)
  }

  R <- gamma_correct(R_lin)
  G <- gamma_correct(G_lin)
  B <- gamma_correct(B_lin)

  # Clip and scale to 0–255
  to_255 <- function(x) round(max(0, min(1, x)) * 255)

  c(R = to_255(R), G = to_255(G), B = to_255(B))
}

# ----------- Step 2: Apply conversion to all rows -----------
rgb_list <- mapply(lab_to_rgb_C, lab_data$L, lab_data$a, lab_data$b)
rgb_matrix <- t(rgb_list)

lab_data$R <- rgb_matrix[,1]
lab_data$G <- rgb_matrix[,2]
lab_data$B <- rgb_matrix[,3]
```

8.8 Graphical abstract

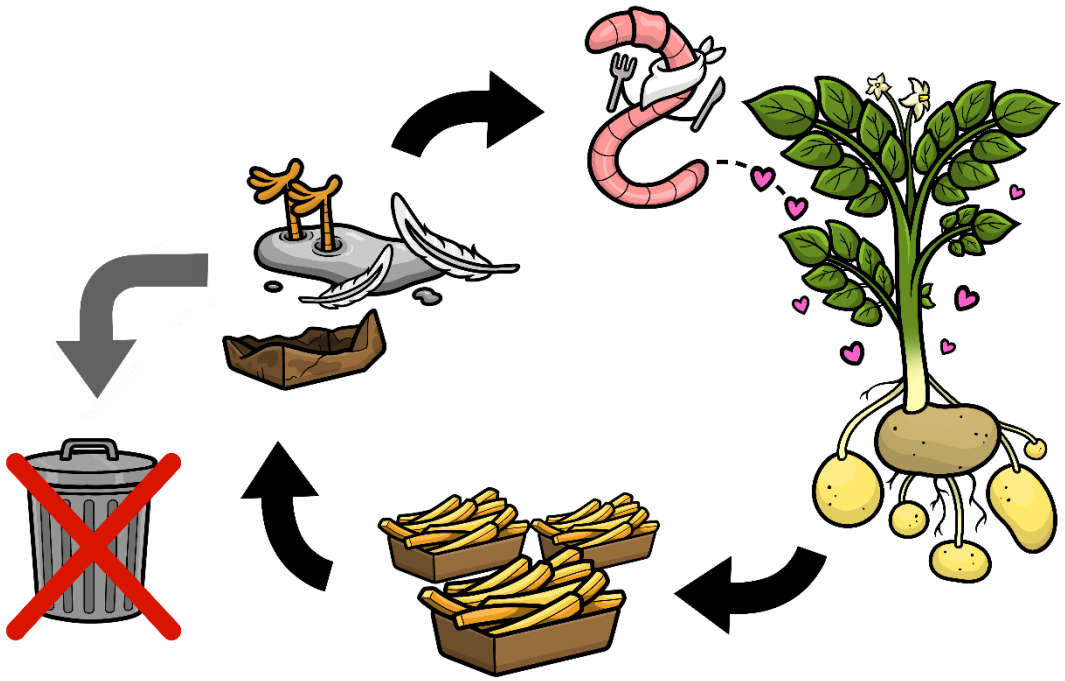


Figure 8-1: 1,000 colourful words. Artwork: Zaria Hemara.