



Reused streams in apple cultivation

In situ impact on soil characteristics, apple growth and rhizosphere microbial community

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Keywords: Circular economy, protists, rhizosphere community, soil chip,
Malus domestica, compost

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Abstract

Modern agriculture and horticulture rely on pesticide and mineral fertilizer use that causes pollution and harm to the environment. With changing climate and legislation, there is pressure to develop more resilient systems. One of the potential ways to limit mineral fertilizer use while creating more stable growing systems is to implement circular nutrient economy in the form of using rest-product compost. As in many other cultures, implementing conventional methods for apple orchards tend to cause soil degradation.

This study investigates the potential of using locally produced rest-product compost as fertilizer and the implications on soil health, growth of apple and the apple rhizosphere microbial community. During nine weeks, apple branches (*Malus domestica*) of root stock A2 were grown in pots in a polytunnel. Treatments consisted of a control grown in apple orchard soil (AOS) and rest-product compost amended orchard soil in a 20:80 ratio (RPC) to match commercial basal fertilization. Control was fertilized with mineral fertilizer. Growth measurements such as longest leaf, number of leaves and accumulated shoot growth were examined as well as soil physical properties before and after cultivation. The microbiome was monitored during cultivation via the microfluidic soilchip and examined under microscope. Abundance of different microbial groups were investigated.

Statistical analyses, including standard least-square and t- tests, were employed to evaluate growth patterns, microbial abundance and soil physical properties. Growth was improved by the amendment of rest-product compost. Significant differences were observed in shoot length and number of leaves. Significant differences were found between the treatments in microbial groups such as hyphae, amoeba, lobose amoeba, ciliophora, and flagellates. These findings suggest that RPC can enhance soil and growth, contributing to more sustainable apple cultivation practices.

Keywords: circular economy, protists, rhizosphere community, soil chip, soil characteristics

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Abbreviations

AOS	Apple orchard soil
EC	Electrical conductivity
IFP	Integrated fruit production
IPM	Integrated pest management
PDMS	Polydimethylsiloxane
RPC	Rest product compost
RPE	Rhizosphere priming effect
SMC	Spent mushroom compost
SOC	Soil organic carbon
SOM	Soil organic matter

1. Introduction

In a more and more informed society, we strive to lower environmental impact from the staple foods we eat on a daily basis. It is said that one apple a day keeps the doctor away, but what can we do to keep the doctor away from the apple?

Just as this proverb, it starts with the health of the organism. Just as feeding a nutritious and healthy apple to a human, making the gut bacteria flourish, the same goes for the apple tree. To keep pesticides and other “medical” treatments away from our trees, we need healthy trees and therefore healthy growing conditions. Not only this, but keeping the bigger picture in mind, we would hopefully achieve this with locally sourced products and to reduce impact even more, wastes could be used.

For an apple tree, *Malus domestica*, to produce harvest, the right nutrients and the right soil are essential (Neilsen & Neilsen 2003). Apple production favors stable soils with a wide range of pore sizes without compact layers and high bulk density (Barden & Neilsen 2003). Aeration and drainage is also important for growing apples, making coarser soils popular for site selection. Since coarser soils often lack significant soil organic matter (SOM) content, organic products are often added. In both these regards, compost could be an alternative.

1.1 Apple production and sustainability

During the last few years, Swedish apple orchards produced around 22'000-30'000 tonnes of apples each year (SBC 2020). Of the circa 1500 ha of Swedish apple orchards, only 300 ha are under organic management (Jordbruksverket 2020). Despite making up around 20% of all area, the organic apple production only stands for around 10% of the total yield with 7,1 tonnes produce/ha compared to the 15,6 tonnes/ha in conventional orchards.

With the oncoming climate crisis and population increase, it is more important than ever to keep up production in a sustainable way (Tilman et al. 2011). However, sustainability cannot only be measured as organic or not (Boone et al. 2019). The following section will explore apple production in Sweden and how it relates to sustainability.

1.1.1 Pesticide use

In year 2016-2017, around 85% of Sweden's 1532 ha commercial apple orchard land were sprayed with pesticides (SBC 2018). Even at current rather controlled use of pesticides, the use of pesticides have the inherent risk of altering and impacting biodiversity in many different species and taxa (Beketov et al. 2013; Pekin 2013; Gibbons et al. 2015). According to Pretty & Bharucha, the costs of pesticide use is often underrepresented, mainly harming communities, farmers and environments both health wise and economically (Pretty & Bharucha 2015). Still, pesticide use is today essential to keep up global food demand.

1.1.2 Mineral fertilizer use

Today's agriculture and horticulture's environmental impact does not only stem from pesticide use. One of the main factors for our agricultural boom was the introduction of fertilization. Since 1990 to 2020, inorganic fertilizer use world wide have rose by 46% to 200 million tonnes per year (FAO 2022). In Sweden, around 185 000 tonnes inorganic nitrogen fertilizer was sold the year 2022 (SBC 2023) and with current world wide use, the mineral fertilizer demand is not expected to go down (Tilman et al. 2011). Excessive use of chemical fertilizers impact the soil and environment in a number of different ways; such as eutrophication and nutrient over pollution (Liu et al. 2014), acidification of soils and water (Guo et al. 2010) and overall lowering of the nitrogen use efficiency for crops and fields (Vanlauwe et al. 2011) as well as limiting microbial soil community activity (Söderström et al. 1983). If this overuse of mineral fertilizers continue, it is estimated that a 2,4-2,7 fold increase of eutrophication in terrestrial, freshwater and marine ecosystems will be seen by 2050 (Tilman et al. 2011).

Nitrogen and phosphorus are often the main constituents in any fertilizer due to their limited availability, causing a restricted plant growth if not manually added (Ågren et al. 2012). Both these minerals are problematic to attain from a sustainable perspective, both causing heavy pollution to the environment. Even if sustainable mineral nitrogen fixation is in development, current nitrogen fertilizers are mainly produced by the heavily fossil-fueled Haber-Bosch process that has been estimated to require 1-2% of the worlds yearly energy supply (Rafiqul et al. 2005; Tanabe & Nishibayashi 2013; Wang et al. 2021). Mineral phosphate fertilizers stem from mining of phosphate rock in environments heavily impacted by the mining, causing biodiversity losses and pollution (Dawson & Hilton 2011; Yang et al. 2014). The mining locations are often far away from Europe and require long transportations, furthering the emissions.

1.2 Circular economy and IPM in horticulture: Compost as a potential fertilizer and soil improvement

Increasing food demand leads to greater nutrient requirements, despite agriculture already being heavily dependent on finite resources and high pollution (Dawson & Hilton 2011; Tilman et al. 2011). This increased demand has put pressure on the agricultural sector, introducing the concept of reusing nutrients. Circular economy in the agricultural and horticultural sector is a rather new concept, focusing on the reuse of biowaste to enrich current cultures instead of using non-renewable mineral fertilizers (Salinas-Velandia et al. 2022).

Following this, in accordance to European law (2009/128/EC), it is expected of producers to reduce pesticide use and to implement integrated pest management (IPM), or in the case of fruit production, integrated fruit production (IFP) (European Parliament 2009). The legal requirement to limit pesticide use pressures producers to develop resilient systems that can handle changing climates and pests without relying on pesticides. This, along with restrictions on mineral fertilizers, pushes for more sustainable agricultural practices.

1.2.1 Compost as an alternative source for organic fertilizer and disease control

In natural environments, essential plant nutrients are stored in organic matter (SOM), making it inaccessible for plants to use. During maturation of compost, organic matter is degraded by microorganisms into more plant-accessible nutrient forms, making the mature compost humus-like, stable and rich in both nutrients and microbes (Aguilar-Paredes et al. 2023). To increase SOM and nutritional as well as physical properties of the soil, organic products such as composts, are often added. Reducing inorganic fertilization by incorporating more organic fertilizers, soil organic matter (SOM) increases (Yang et al. 2011; Li et al. 2020).

All living things, including plants, are colonized by microbes. It has been shown that different tissues, species, ages and life stages, host different microbiomes, therefore fostering different microbial communities (Edwards et al. 2015; de Souza et al. 2016; Schlemper et al. 2017; Arrigoni et al. 2018; Wu et al. 2020; Huang et al. 2023). Following this, the rhizosphere itself is an environment rich with microbes, due to sugar-rich root exudates that form a favourable habitat for microbes (Lynch & Whipps 1990). As in all ecosystems, all integral parts influence each other in their interactions. Even if microbes are small and might seem insignificant, they make up 5% of the organic matter in soil (Dalal 1998). The combined effect of the soil rhizosphere can heavily influence plants to either thrive or not survive.

It has been shown that adding compost in apple orchard soil increases bacterial community diversity and microbial biomass, boost apple productivity and increase

soil fertility (Thompson et al. 2019; Zhu et al. 2020; Kai & Adhikari 2021; Sharaf et al. 2021; Wang et al. 2022).

Even just substituting part of the fertilization regime with organic amendments has been proven to increase microbial diversity in the soil, particularly the nutrition cycling taxa (Kramer et al. 2006; Tang et al. 2022). Not only this, but it is more environmentally sustainable. This is due to the increased amounts of soil organic carbon (SOC) in soil after organic amendments (Yang et al. 2015; Jiang et al. 2018), reducing acidification and favoring nutrient cycling microbial taxa (Tang et al. 2022).

Rhizosphere priming effect

During cultivation, SOM generally decreases (Bongiovanni & Lobartini 2006; Schnitzer et al. 2006). Plants can modify the released root exudates, therefore modifying their environment and impacting the rhizosphere communities (Canarini et al. 2019). This decreased degradation of SOM during cultivation is partly because of microorganisms in connection to plants can have a so called rhizosphere priming effect (RPE). The RPE stems from root exudates from the plant stimulating microbes to degrade SOM (Huo et al. 2017). In woody species, such as apple, the RPE is especially apparent (Huo et al. 2017). Since it leads to quicker SOM degradation, this causes a slow release of nutrients to the tree during cultivation (Bengtson et al. 2012). However, without SOM in the soil, this priming effect goes to waste, potentially limiting plant available N (Dijkstra et al. 2009, 2013). Solely adding mineral N fertilization could potentially limit SOM decomposition and limit soil microbial biomass (Zang et al. 2016; Murphy et al. 2017).

Compost suppression potential towards plant diseases

Due to the high abundance of microbes in compost, compost microbial communities have long been under investigation for potential disease suppressing abilities. Microbial disease suppressing agents have been isolated from compost and found to be suppressive against, to name a few, *Pythium* in cucumber (Yu et al. 2015), *Fusarium oxysporum* f.sp. *melonis* in melon cultivation (Suárez-Estrella et al. 2013; De Corato et al. 2018) and *Xanthomonas campestris* pv. *vesicatoria* in *Solanaceae* crops (Suárez-Estrella et al. 2019).

1.2.2 Challenges in using compost

However, adding composts does not only increase nutritional values but also electrical conductivity (EC) (Hernández et al. 2015). Previous experiments with compost as a fertilizer have reported excess salt stress of plants (Chaoui et al. 2003;

Pittaway 2014). A lot of composts are also contaminated with heavy metals that could influence growth of plants (Zennaro et al. 2005).

Using compost and circular economy could be a part of the solution for making cultivation more sustainable, but at current fertilizer need, compost could not solely sustain the nutrient need.

1.3 Challenges in apple cultivation

As with most heavily cultivated soils, orchard soils face significant soil degradation when operated under more conventional management (Nielsen et al. 2014; Daelemans et al. 2022). As previously mentioned, cultivation degrades the SOM content, especially in tree cultivation (Huo et al. 2017). The negative impact of conventional systems has been highlighted and the need for more circular and improved conventional systems has been under debate (Glover et al. 2000). It has been shown that implementing more organic and circular practices can improve the soil quality of the orchard site as well as improve tree and yield quality (Glover et al. 2000; Daelemans et al. 2022).

1.4 Engineering a low impact compost for apple

In the current work, three different organic rest products are examined in their potential and availability and are described further in the following section. To further explore sustainability, composting materials should be readily available and produced locally to reduce transports and minimize waste from the agricultural sectors.

To engineer a low impact compost, other locally produced rest-product organic material can be used. In this section, the raw materials used for the compost will be described shortly and are illustrated in Fig 1.

1.4.1 Fruit waste

Due to storage diseases, the apple industry produces big amounts of fruit waste every year, as described in previous section (Sjöstrand et al. 2021). It is estimated that in the primary production of apples, 18% of the full yield is left on the trees and in storage, 2% of the harvested yield is thrown away due to storage spoilage or not meeting quality standards (Olsson et al. 2015). Today, this waste goes relatively unused.

Along with fruit waste, other waste is also produced during the lifecycle of an orchard. During the apple grower's year, regular pruning and thinnings are

maintained to keep up production (Ferree & Schupp 2003). Despite being a perennial crop, orchards still have an economic lifespan when trees need to be cut down and reestablished to maintain production. These activities produce a lot of waste that goes relatively unused.

The fruit waste in and of itself is rich in sugars in the form of glucose, fructose and sucrose (Gullón et al. 2007). As another part of fruit waste comes apple pomace, a restproduct from juicing of apples (Costa et al. 2022). About 25% of produced apples are processed for juicing, leaving about 25-30% of the initial biomass as apple pomace to be disposed of (Costa et al. 2022). In this thesis, only fruit waste from storage and apples that do not meet quality standards are used, but apple pomace could also be a potential candidate for raw material in the future.

1.4.2 Spent mushroom compost (SMC)

Nowadays, spent mushroom compost (SMC), a rest-product compost from mushroom cultivation, is used as an amendment in many apple orchards to improve nutrition and soil organic matter contents. Since SMC is high in salt contents, it is not optimal to add directly to the soil of apple orchards and needs to be mixed with other plant material for best effect since apple trees are saltsensitive (Lemaire et al. 1985; Uzun 2004). It has been shown that putting pure SMC in apple soil reduces apple yield (tSaoir & Mansfield 2000), which is why it is advised to mix the SMC with other raw materials before use.

1.4.3 Wood chips

To maintain tree integrity and orchard productivity, pruning and thinning are regular activities in orchards (Ferree & Schupp 2003). These activities, as well as the felling and reestablishment of new orchard trees due to economic lifespan of 12-25 years results in significant restproduct woody raw material (Alaphilippe et al. 2016).

Because wood being naturally made up of carbon-rich cellulose, adding wood chips to a compost brings in large amounts of carbon which when added to agricultural soil, can raise soil organic carbon (SOC) levels which greatly affects soil fertility (Pizzeghello et al. 2021). It has been shown that amendment with compost and wood scraps to soils with decreasing SOC can improve SOC stock and biological and biochemical activities of the soil along with increased crop yields (Bonanomi et al. 2014). Along with improving SOC stock, adding wood chips has been shown to reduce soil compaction (Wolf et al. 2019) and can stabilize soil aggregates over longer periods of time (Abiven et al. 2009).

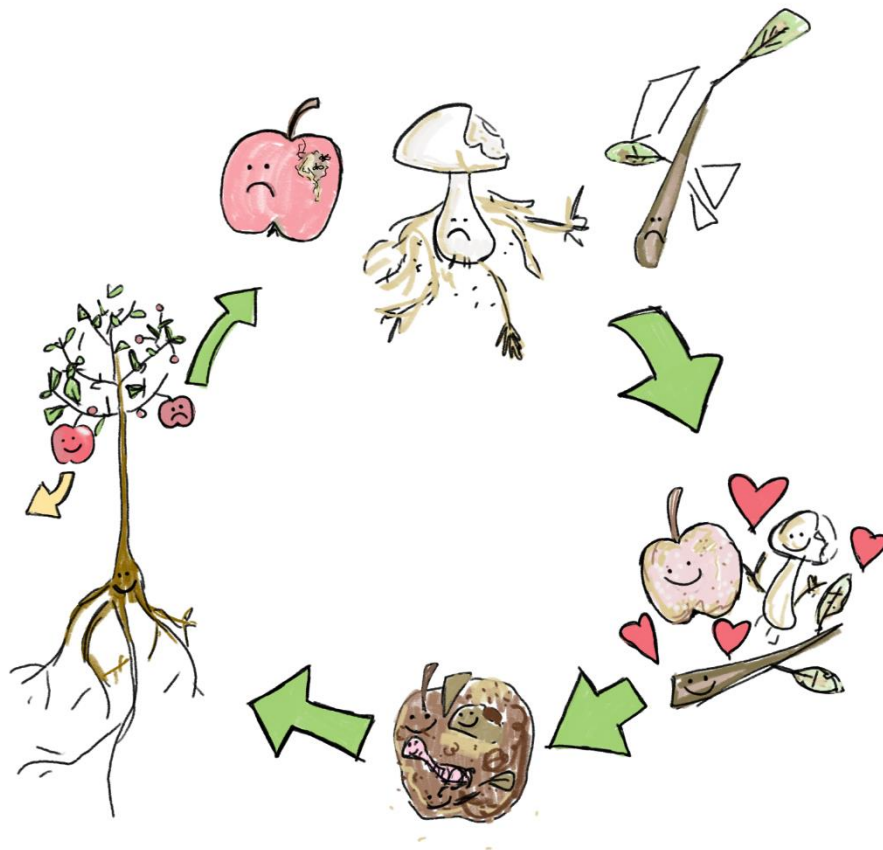


Figure 1: Descriptive figure of the circular economy of rest product compost used in apple cultivation, made from wood chips, spent mushroom compost (SMC) and apple fruit waste. Illustration by author, Julia Forsbacka.

1.5 Aim

The overall aim of this work is to evaluate the potential implementation of circular economy in apple cultivation as a tool to improve soil health and production. The aim of this project is to investigate the potential of using rest product compost (apple waste, spent mushroom compost and wood chips) as a full basal fertilizer in apple cultivation and its effect on the growth of apple tree and on the rhizosphere microbial population as well as on the physical parameters of soil with and without compost amendment. The focus is on the evaluation of *Malus domestica* root stock Alnarp 2 (A.2.) and the rhizosphere microbial population and composition, using SoilChips to gather a full picture of the cultivation and changes the compost bring to the whole system.

The hypothesis driving this investigation are the following;

- Rest product compost amendment works as a full basal fertilizer in apple cultivation of apple root stock A.2. for 8 weeks.
- Rest product compost amendment boosts microbial diversity and abundance compared to native orchard soil fertilized by mineral fertilizer, especially an initial boost after amendment.
- Rest product compost amendment improves soil structure and soil characteristics such as water holding capacity, porosity and bulk density in native orchard soil fertilized by mineral fertilizer.

2. Material and methods

This thesis investigates whether the utilization of locally produced rest-product compost derived from horticultural residues can enhance soil health and therefore improve plant health in apple tree cultivation. Microbial diversity and apple growth bioassays were used as indicators. The experiment was run for 6 weeks in a polytunnel at Trädgårdslaboratoriet at the Swedish Agricultural University (SLU), Alnarp, Sweden, during May 31st to the 1st of August 2023. During cultivation, growth parameters of the apple trees was monitored continuously and microbial diversity was examined at three separate time points (week 2, 4 and 6). Soil characteristics along with nutrient analysis of soil was examined pre- and postcultivation.

2.1 Rest-product compost and soil

As part of a bigger project in collaboration with Äppelriket, Kivik, three different composts with different proportions of apple fruit waste, wood shavings and SMC were prepared. The composts were allowed to mature and develop for 12 month at the Högestad Christinehofs orchard in Kivik, Sweden (table 1). They were then investigated to find the best candidate for the examination.

Table 1: The composition of different types of composts proportioned with different composition of spent mushroom compost, apple fruit waste and wood chips that was pre-screened for their potential on growth parameters during apple branch cultivation.

Compost name	SMC	Apple fruit waste	Wood shavings
4	33%	33%	33%
5	50%	25%	25%
6	20%	40%	40%

Two treatments were used, one control with apple branches being grown in apple orchard soil (AOS) and one treated with the rest-product compost (RPC) in a ratio to match full basal fertilization. The ratio and nutritional status is described in the following section.

Orchard soil was used as control treatment along with mixing compost. The soil used in this investigation was collected from Högestad Christinehofs orchards in

Kivik (Fig 2A). The orchard Högestad Christinehof is part of the bigger grower collective of Äppelriket, Kivik, Skåne, Sweden. Soil was collected during two separate occasions, first in March and later in May. As to avoid damage to current apple cultivation, top soil was carefully removed between trees in the same row. This was then stored in a cold room along with the compost collected in May until use (Fig 2B).

2.1.1 Nutrient content

In this experiment, all pots recieved basal fertilization at 30 kg N/ha as advised by Dominik Merkert, advisor at Äppelriket.

To determine the amount of compost needed to reach basal fertilization, nutrient contents were examined. Three replicates of each compost (around 500g/replicate) were sent to LMI (Helsingborg, Sweden) for nutrient analyses using Spurway-analysis method.

Based on the nutrient compositions and electrical conductivity (EC), the most suitable compost was selected for cultivation and the amount of compost was calculated to ensure optimal nutrient level. It was determined that using compost 5 in a 20:80 ratio with apple orchard soil was the best candidate. The control treatment being grown in the apple orchard soil recieved Osmocot (NPK 15-9-12) to match basal fertilization.

Calculations and results of preliminary nutrient analysis can be found in Appendix 1.

2.2 Plant material

The cold resistant apple rootstock Alnarp 2 (A.2.) was used as the bioassay as it is a hardy and fast growing root stock. A.2. apple branches that had been stored in a cold room were placed outside in water for three days prior to planting as to break dormancy.

Before planting in 7,5 l pots, the roots of the A.2. branches were trimmed. Once placed in the pot with soil, the apple branches were cut to equal length, measured from the top of the pot. Amount of growth nodes over soil was noted.

2.3 Soil chip manufacturing and stabilization

SoilChips are a type of microfluidic chips used to investigate soil microbes, invented at the Microbial Ecology group led by Edith Hammer at the Biology department of Lund University. The SoilChips use polydimethylsiloxane (PDMS) to replicate soil structures. The PDMS slab is bonded to a glass cover slide, letting

microbes enter and colonize the chips while enabling easy access to the inner workings of the soil through microscopy. These chips were manufactured at Lund University.

2.3.1 Manufacturing of SoilChips

The SoilChip ‘Obstacle’ was originally designed by Aleklett et al. (2018) and were manufactured in accordance to their protocol (Fig. 2C). To create the slab with structures, SYLGARD™ 184 Silicone Elastomer Kit (DOW Europe, Germany) was used. A 10:1 ratio of PDMS mix to curing agent was used. The mixture was stirred until white and poured onto the ‘Obstacle’ chip master for molding. To remove air bubbles, the mold with PDMS was placed in a vacuum chamber for 45 minutes and then transferred to a 70°C oven for 120 minutes to ensure polymerization. The resulting slabs were subsequently cut from the master and placed on a clean glass slide (54x70mm, 0,13-0,16mm), with the structured side facing down.

To bond and seal the slab with a glass cover slide, a vacuum oven is used to activate the surfaces. A clean glass cover slide was blasted with plasma for 60 seconds. The slab, now with structured side up was placed in plasma oven alongside the already activated cover slide. Both slide and slab was activated by plasma for 18 seconds. The two now activated surfaces was then placed together and sealed before being placed on a 70°C heating block for 4 min to ensure good bonding between surfaces.

2.3.2 Stabilizing chips before placement

To avoid breaking under the weight of the soil, the chips needed to be secured and stabilized. This was done in accordance to Karlsson (2022). Chips was placed on a 80x55mm plastic slab, stabilized by taping it down (Fig. 2C).

One day after apple culture establishment, soil chips were activated in plasma chamber for 60 seconds to become hydrophilic and was then filled with 100 µl distilled water. They were then wrapped in bubble plastic over the top as to further distribute the weight of the soil (Fig. 2D). After this, the water-filled chips were placed in a container with wet paper towels as to create a humid environment for transportation and prevent chips from drying out.

2.3.3 Chip placement

Four chips were placed in each pot, about halfway down. Soil was moist when placed as to further prevent chips drying out. Chip opening was placed towards the middle of the pot (Fig. 2D).

To not loose sight of the chip placement, string was attached to the chip and left out (Fig. 2D).



Figure 2: A) Sandy clay soil from the Högesta Christinehofs orchard in Kivik, Skåne, Sweden, used as control in experiment Apple orchard soil = AOS. B) Treatment of apple orchard soil amended with rest-product compost (RPC), ratio of 20:80 compost:soil. C) Complete and stabilized soil microfluid soilchip. D) soilchip placed in pot, covered in bubble plastic to further redistribute weight of the soil as to not make chip break. Note that opening of chip is not covered in bubble plastic to allow microbes to enter. Four chips were placed in each pot, six biological replicates of each treatment. All pictures by author Julia Forsbacka, 2023.

2.4 Polytunnel and experimental setup

To further prevent chips and apple trees drying out, drip irrigation was installed. Each plant received four separate drip irrigations, in a so called spider dripper, with the drip placed above chip opening. Plants were irrigated for 8 minutes four times a day, rounding out to about 1 liter of water per pot per day. Irrigation occurred at 7:00, 11:00, 15:00 and 18:00 o'clock.

After planting, pots and apple trees were placed randomly in two rows with about 20-30 cm of space between pots (Fig 3).

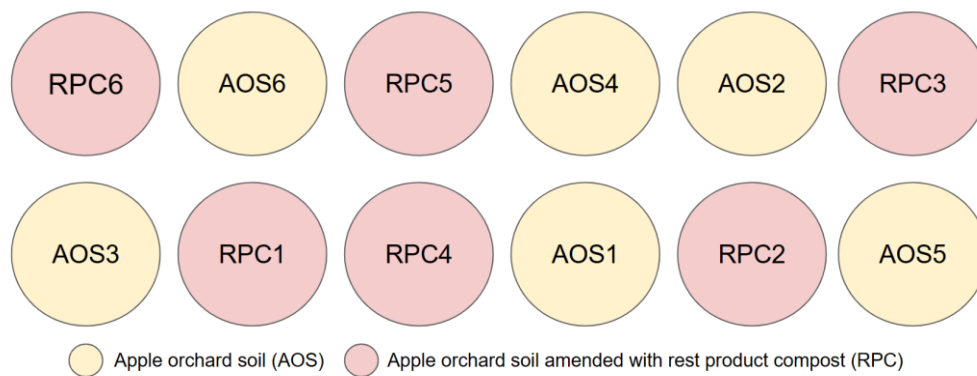


Figure 3: Experimental setup of apple tree pot experiment in polytunnel with randomized placement of six biological replicates for each treatment. Treatments include control of apple orchard soil (AOS) and soil amended with rest product compost (RPC) in a 80:20 ratio (AOS:RPC).

2.5 Data collection

2.5.1 Bioassay

During cultivation

Growth was measured during cultivation along with moisture contents in soil. Moisture contents was measured weekly.

Growth parameters were noted every 2-3 days and can be found in table 2.

Table 2: Growth parameters to be investigated during nine week apple branch cultivation in pots. Treatments include apple orchard soil as control and rest-product compost amended apple orchard soil.

Parameter	Measured
Developed buds	N:o developed buds
Leaves	N:o leaves
Longest leaf	Length of longest leaf (cm)
Longest shoot	Length of longest shoot (cm)
Damage	N:o leaves damaged by insects or disease, grouped by damaging vector

Leaf, shoot and root fresh and dry weight

After cultivation, trees were carefully removed from the pots as to not break fine roots. The roots were then cleaned under water and examined before being cut off and put into foil packets. The leaves were removed from the trees and put in foil. The shoot were cut into pieces and also put into foil. The fresh weights were noted before being put into an oven. After 48 hours at 70°C, the dry weight was noted.

2.5.1 Nutritional values and physical soil parameters

Physical parameters such as bulk density, compact density and water holding capacity was examined both before culture establishment and after harvest along with Spurway nutrient analysis done by LMI (Helsingborg, Sweden), as previously mentioned.

Bulk density was measured using a bulk density apparatus containing a 0,9 dm³ cylinder, an extra ring to extend the height of the cylinder and a small weight. The soils were put into the cylinder and weight was placed to compact soil for 3 minutes. After this, soil was weighed and bulk density calculated.

Compact density was measured using 90% Ethanol. A 100 ml flask was filled halfway with soil and 50 ml of Ethanol was added. This was then shaken for 30 minutes before alcohol was added until volume reached 100 ml mark. Then, compact density and porosity was calculated.

Water holding capacity was measured by placing a 0,9 dm³ pot filled with soil in water until completely soaked. The pot was then left to drain for 24 hours before the soil was weighed and then placed in a 105°C oven until dry. Once dry, weight was noted and water holding capacity as well as percentage of water filled pores was calculated.

2.5.2 Microbial observations by SoilChips

Microbial abundance was investigated by the use of the SoilChips placed in the pot during culture establishment. For each one of the three timepoints, one chip was carefully removed from each pot at Trädgårdslabbet and transported to the microscope at Lund University. Here the chips were examined under an inverted microscope at 40x magnification. In the entry pillar-system, microbial observations were made between the third and second to last row of pillars. In this row (approximately 200µm wide), all protists and nematodes crossing were counted. Protists and nematodes were divided into subgroups (table 3). Number of hyphae crossing the specific section was also noted. Interesting protists and other microbes were noted and documented.

Table 3: Groups of microbes to be noted during ocular examination under microscope of microfluidic SoilChips placed in apple branch pots. Chips were examined during cultivation with treatment apple orchard soil as control and rest-product compost amended apple orchard soil with six biological replicates for each treatment.

Group	Subgroups	Fig	Notes or deviations from counting
Hyphae		12a)	N:o hyphae crossing section
Amoeba	General amoeba	9	General amoeba, for example flagellated amoeba that cannot be divided into other more distinct groups
	Lobose	9a)	
	Filose	9b)	
	Granofilose		
	Granoreticulose		
	Heliozoa	12b)	
Ciliphora	Ciliate	11	
	Hypotricha		
Flagellata	Malomonas	10	
	Apusomonada		
Nematoda		13	
Cysts		12d)	
Diatoms		12c)	Despite not making up a distinct phylogenic group, diatoms were noted as a separate category due to their distinct morphological appearance.

Bacterial abundance

Bacterial abundance was counted by using a neural network developed by the Soil Chip team at Lund University, as described by Zou et al. (2024). The neural network was fed pictures taken during microbial observation analysis and counted the bacteria present. The pictures used for counting was taken using the job function in NIS elements and was set up to take photos of 10 random spots between the second and third to last row in the entry pillar system, with five different depths. The classes counted in the neural networks were single bacteria, dividing bacteria (two bacteria) and clusters of bacteria (more than three). The number of bacteria in the clusters were calculated by using the average size of bacteria in the given picture.

2.6 Statistics

Statistical tests were performed in Rstudio 2022.07.2+576 and JMP 17.

3. Results

3.1 Bioassay

The following sections highlights the difference in growth across the treatments. After cultivation, the trees were removed from the pot and the roots were cleaned. In the picture below, the differences between the treatments can easily be seen with the naked eye (Fig 4), but are further explored in the section.



Figure 4: Apple trees post-cultivation of approximately two months in polytunnel with different soil treatments: i) apple orchard soil (AOS) and ii) root stocks cultivated in apple orchard soil amended with rest-product compost (RPC) in a ratio of 20:80 (RPC:AOS). Six biological replicates was used, number in picture notes the replicate.

Growth, as measured by leaf count, deviated between treatments. Initial growth were similar across treatments but during cultivation, growth of the RPC treatment deviated (Fig 5a). Approximately one month after culture initiation, this deviation started to occur and there was a steady difference between treatments across the rest of the growing season, with RPC showing stronger growth (Fig 5a).

Similar trends were observed by length of longest leaf and length of longest shoot, where RPC treatment showed stronger growth trends (Fig 5b). Initially, both treatments grew at similar rates but during cultivation, differentiation occurred, especially in length of longest shoot. A slight difference in leaf length can be observed (Fig 5b). Not only were the longest shoot of each tree significantly different between treatments, but also sum of all shoot growth as measured by the end of cultivation, where RPC treatment had accumulated more shoot growth than AOS (Fig 5c).

After cultivation, fresh weight of leaves, stems and roots varied between treatments significantly (Fig 5d). However once dry, weight only varied significantly between treatments in leaves, meaning that the biggest difference in fresh weight between treatments were from moisture in the stems and roots. The average dry leaf of AOS weighed 59 mg and of RPC 74 mg.

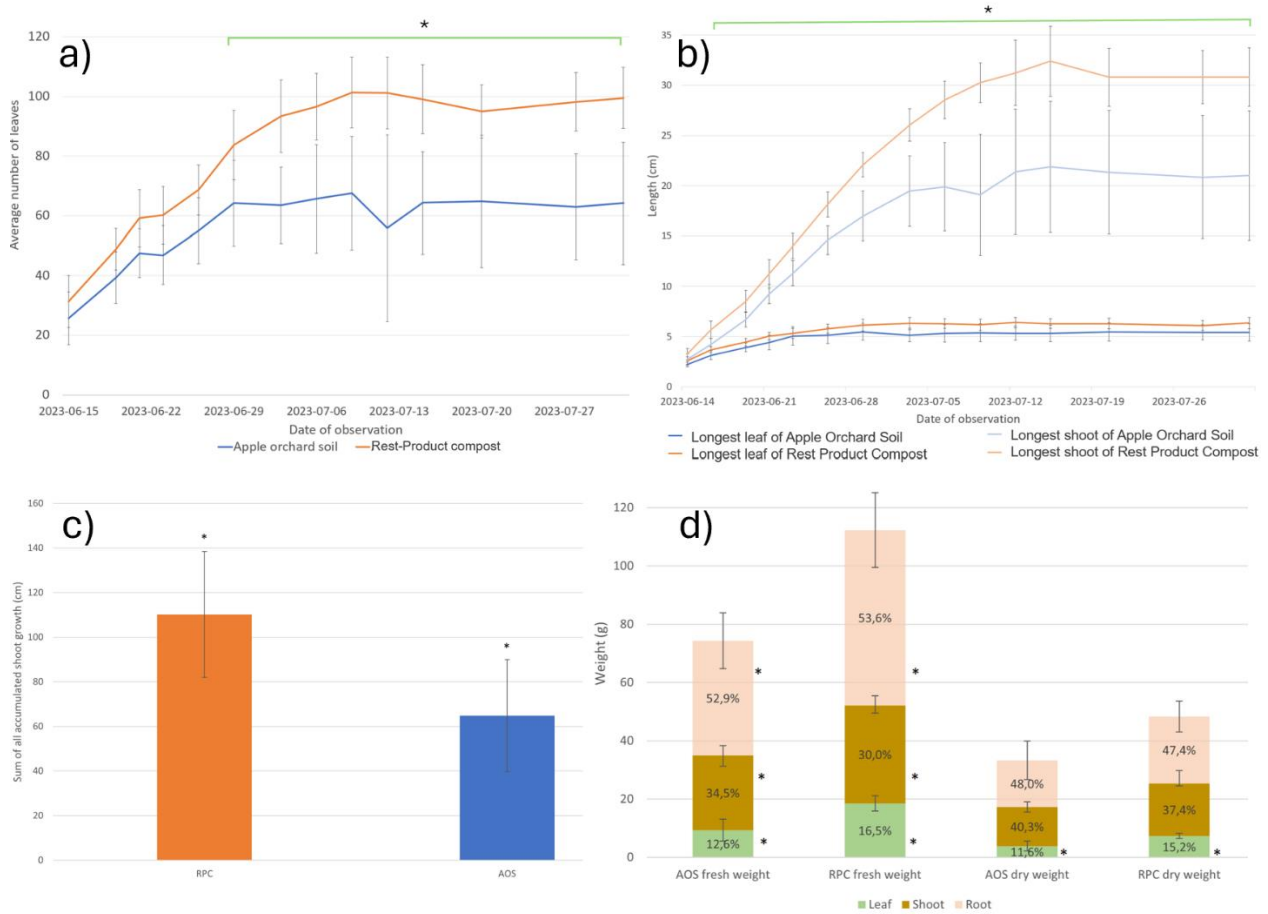


Figure 5: Growth measurements of apple trees of root stock A2 grown in pots in polytunnel for 9 weeks. Treatments include a control of Apple orchard soil (AOS) and a rest-product compost treatment with a 20:80 ratio of compost to apple orchard soil (RPC). Six biological replicates was used. Star indicates a significant difference between treatments ($p < 0,05$) in t -test. A) Average number of leaves B) Longest shoot and leaf; significance refers to shoot only. C) Sum of accumulated shoot post-cultivation. D) Fresh and dry weight post-cultivation. No significant difference in proportions.

3.2 Physical soil parameters before and after cultivation

3.2.1 Soil physical characteristics

Bulk and compact density as well as porosity of soils used in experiment changed significantly during cultivation (Table 4). Both AOS and RPC treatment increased bulk density post cultivation, however AOS compact density decreased during cultivation while RPC increased. This leads to AOS having an increased porosity post cultivation while RPC decreased.

Table 4: Physical characteristics of soil before and after nine weeks of apple cultivation in pot experiment. Treatments include AOS = Apple orchard soil and RPC = rest product compost in a ratio of 20:80 (AOS:RPC). Six biological replicates were used for each treatment. Treatments that do not share a letter are significantly different as investigated by post-Hoc Tukey ($P > 0,05$).

	Bulk density (g)	Compact density (g)	Porosity (%)	Water holding capacity (%)	Water filled pores (%)
AOS pre cultivation	1117,2 ^a	2280,5 ^e	48,99% ^h	35,56% ^l	72,58% ⁿ
AOS post cultivation	1161,1 ^b	2183,4 ^f	53,33% ⁱ	34,65% ^l	65,15% ^o
RPC pre cultivation	899 ^c	1425,4 ^g	61,56% ^j	41,91% ^m	68,09% ⁿ
RPC post cultivation	1015,6 ^d	2103,6 ^f	48,38% ^k	35,47% ^l	73,91% ⁿ

3.2.2 Nutrient contents

Initially, the RPC treatment exhibited higher levels of phosphorus, potassium, magnesium, sulfur, and calcium compared to AOS (Fig 9). Over the cultivation period, these nutrient levels in decreased both treatments. However, both treatments maintained similar nitrogen contents throughout the cultivation period, even with the decrease after cultivation. Micronutrient levels, including manganese, boron, and iron, were relatively low in both over the whole period. Sodium levels, initially high in both treatments, exhibited a significant decrease post-cultivation, particularly in the RPC treatment (Fig 7).

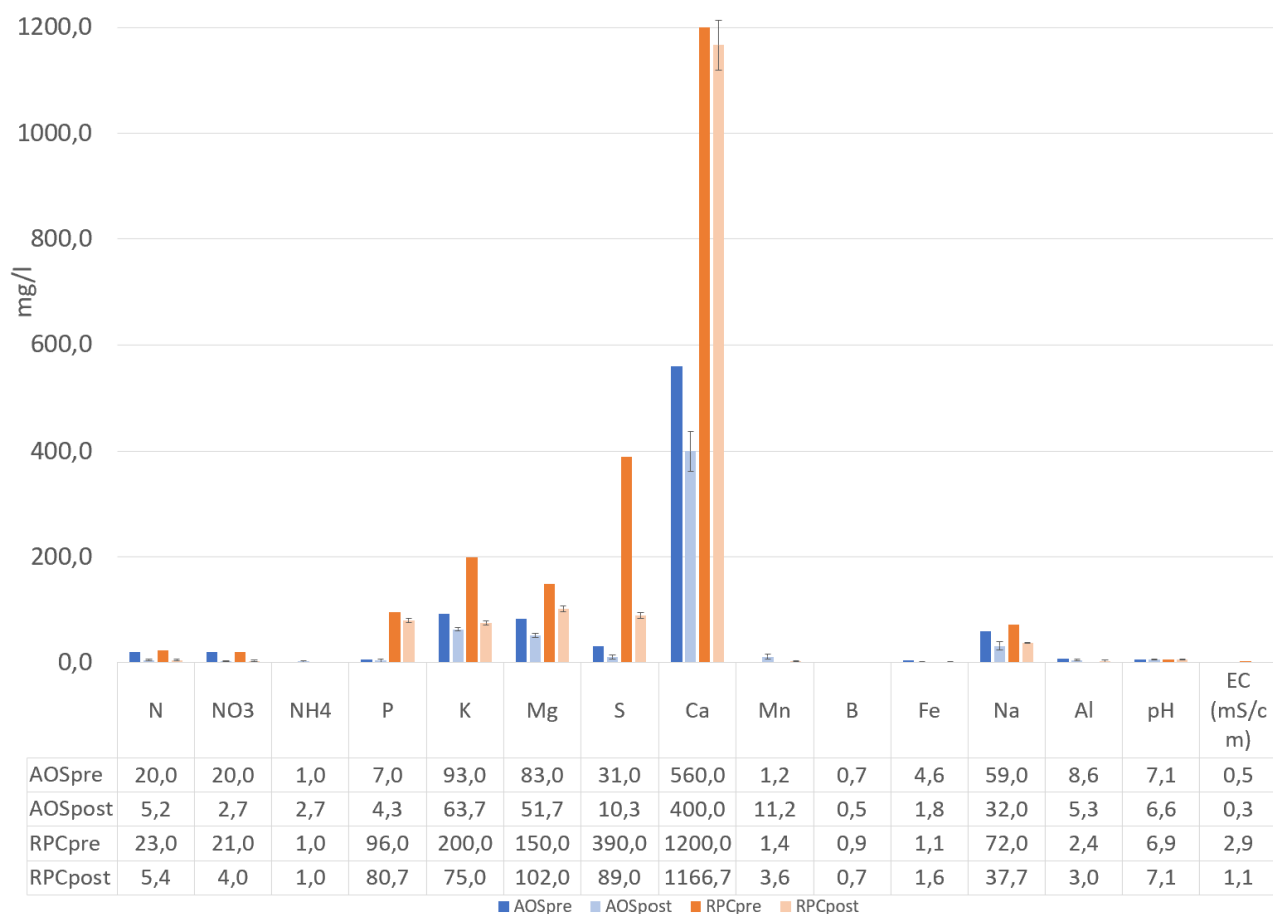


Figure 6: Plant-available nutrients in soil pre and post-cultivation in two treatments, apple orchard soil (AOS) and rest product compost amended soil (RPC) pre- and postcultivation. Apple trees were grown in pots for nine weeks, six biological replicates were used. Samples were pooled to three samples for each treatment post-cultivation. Pre-cultivation, only one pooled sample was sent off. Plant nutrient analysis was done by LMI (Helsingborg, Sweden) by Spurway analysis.

3.3 Microbial abundance during cultivation

Employing standard least-square analysis, significantly higher abundance was shown in RPC treatment across multiple microbial groups, including hyphae, amoeba, lobose amoeba, ciliophora and flagellates (Fig 8a; 8b). Further, as hypothesised, microbial abundance was significantly higher in the RPC treatment during the first time point and then further along the growing process, the abundance between treatments were more similar (Fig 8a).

Microbial abundance in SoilChips were log-transformed due to Shapiro-Wilks test showing this being a good fit.

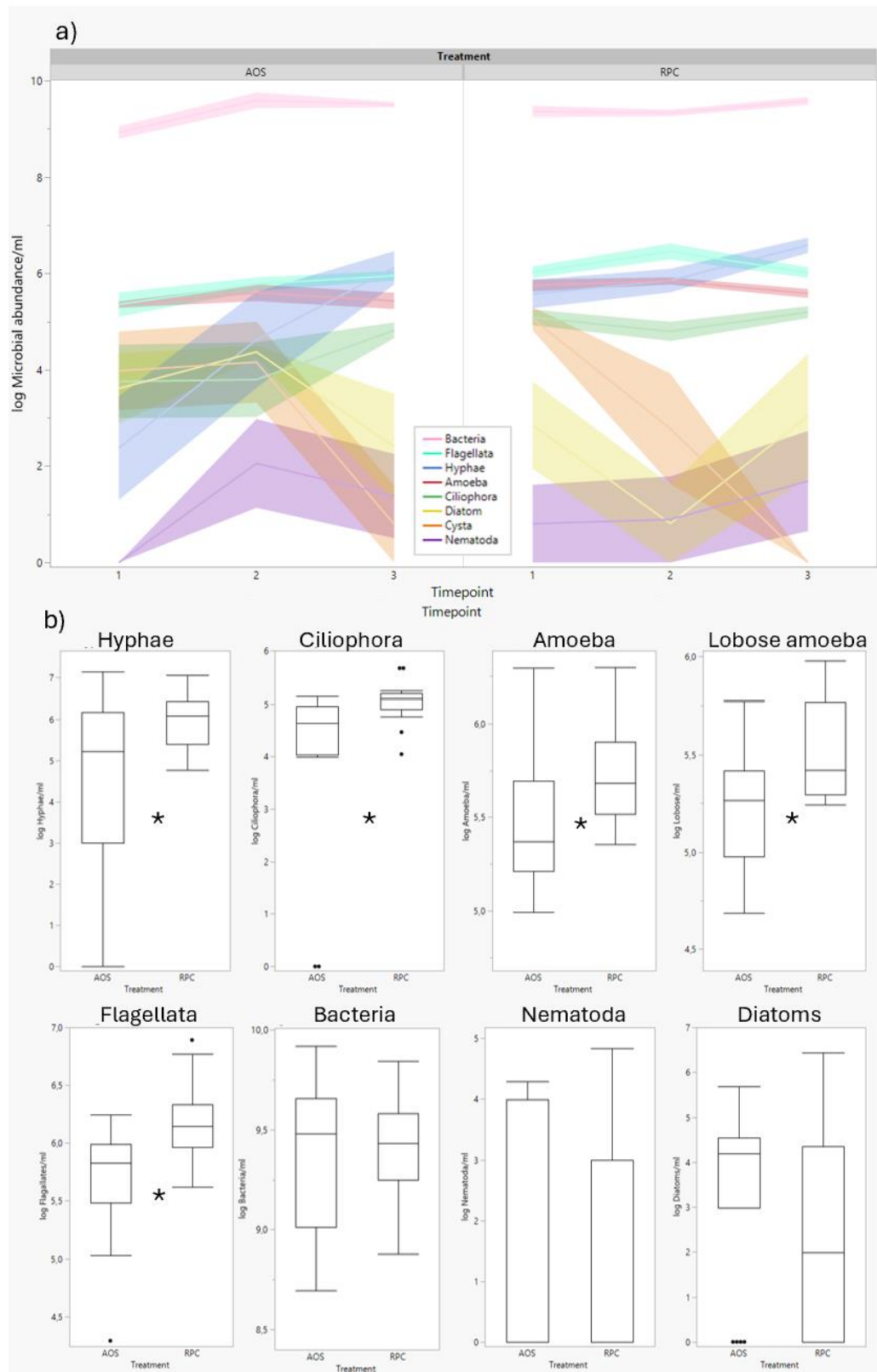


Figure 7: Microbial abundance in apple pot cultivation during 9 week long experiment. Two treatments were used, a control with apple orchard soil (AOS) and rest-product compost amended soil (RPC). 6 biological replicates were used. Microbial abundance was measured using microfluidic soil chips that were placed in the pots at the beginning of cultivation and removed for examination. Microbial abundance was log-transformed to attain statistical model with good fit, as tested by Shapiro-Wilks test. a) Microbial abundance over cultivation period. Timepoint 1 is 2 weeks after culture initiation, 2 after 4 weeks and 3 after 6 weeks. The error band represents standard error. b) Microbial abundance in relation to treatment and microbial group. Star indicates a significant difference between treatments according to a standard least-square analysis ($p < 0.05$).

3.4 Microbial observations

Following the microscopy-based analysis of the SoilChips, here is a closer look into what was observed in the chips along with other notable groups of protists and taxa found in the soil.

As previously mentioned, amoeba was significantly different between treatments. The groups noted in this thesis are shown below (Fig 9).

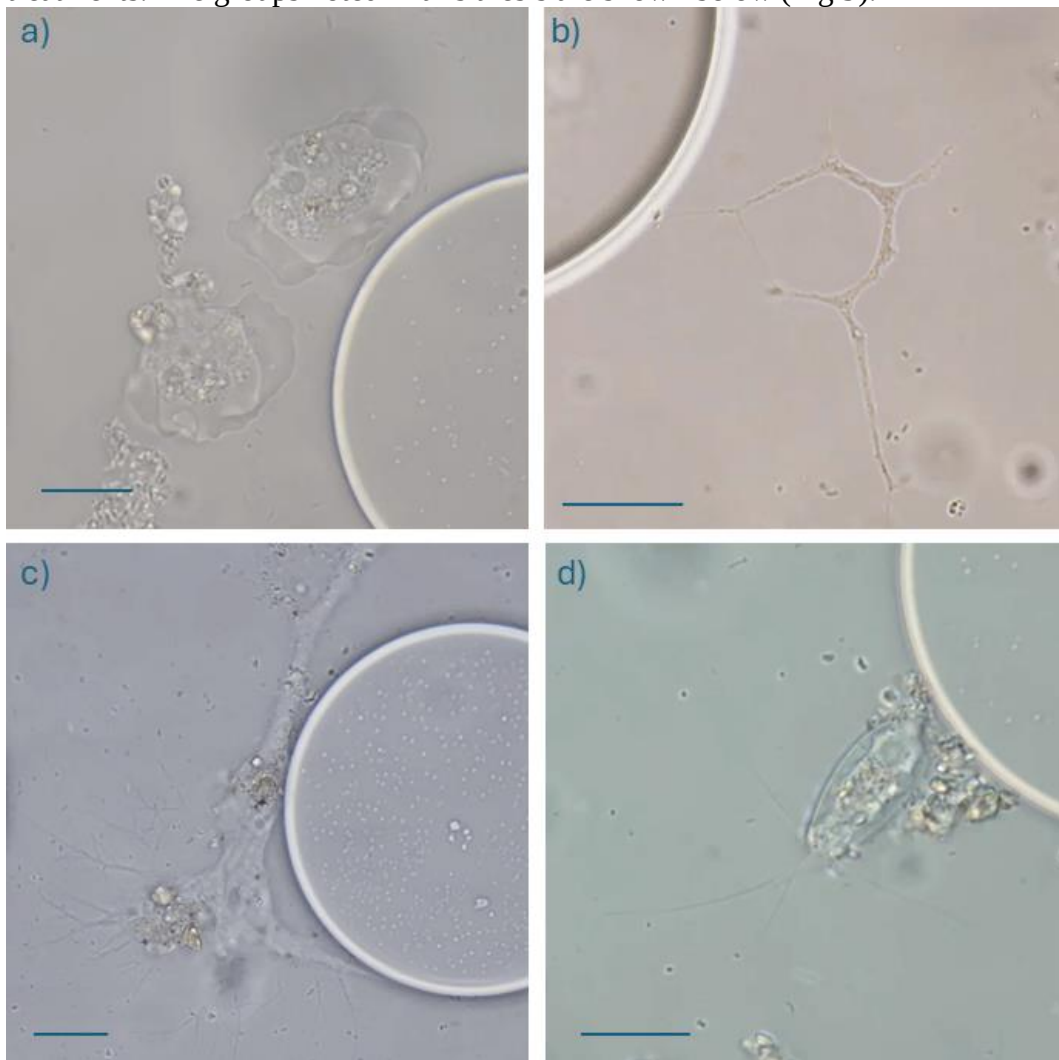


Figure 8: Examples of amoeba found in soil during a nine week cultivation of *Malus domestica* with two treatments Apple orchard soil (AOS) and Rest-product compost (RPC). The photos are taken inside of SoilChips, a microfluidic chip made of PDMS to replicate soil structures. A) Filose amoeba, found in treatment AOS4 at timepoint 3. B) Filose amoeba, found in RPC4 timepoint 2. C) Arbose filose amoeba, in AOS1 timepoint 1 and D) Testate amoeba found in AOS4 at timepoint 3. Blue bar for scale at 20 μ m.

Flagellate abundance was also increased by the compost treatment. The following are a few of the protists grouped under flagellates (Fig 10).

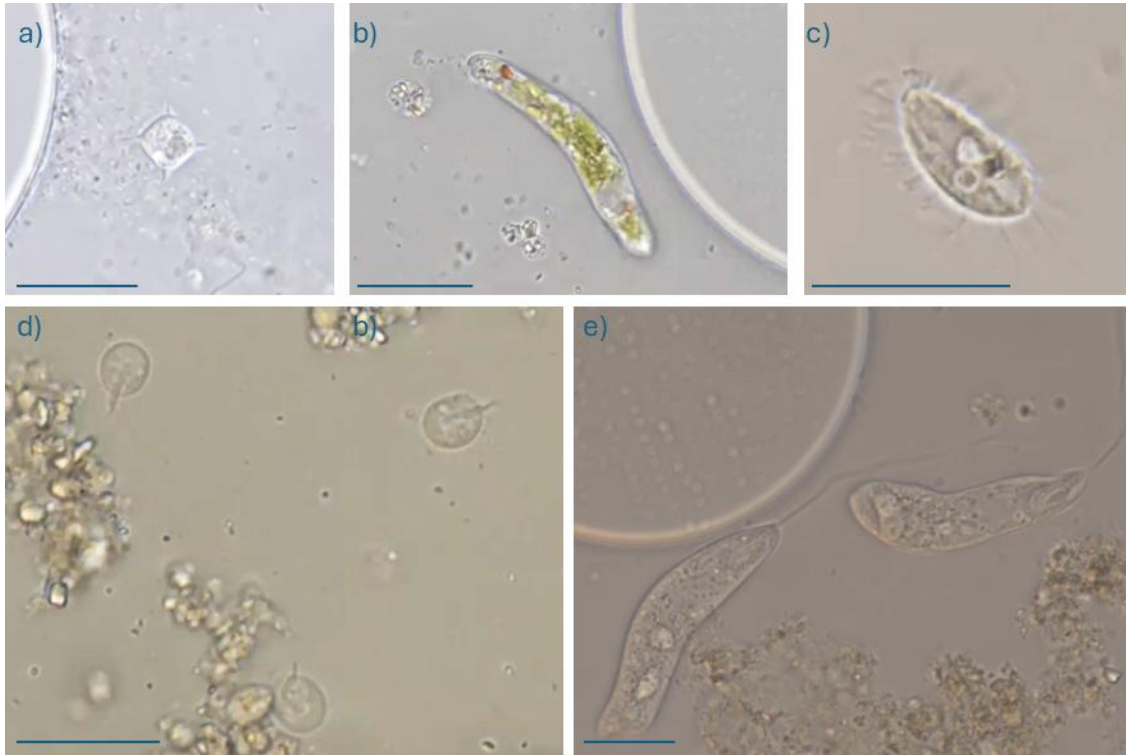


Figure 9: Examples of flagellates found in soil during a nine week cultivation of *Malus domestica* with two treatments Apple orchard soil (AOS) and Rest-product compost (RPC). The photos are taken inside of SoilChips, a microfluidic chip made of PDMS to replicate soil structures. The following groups of protists are identified by a layman and can be wrong. A) *Dichtyochales*, found in RPC4 at timepoint 3 b) *Euglenozoa*, found in RPC5 at timepoint 3 c) *Malomonas*, found in AOS4 at timepoint 3 d) *Apusomonas*, found at AOS4 at timepoint 3 e) *Paranema*, found in RPC1 at timepoint 2. Blue bar for scale at 20 μ m.

Ciliophora was also significant between treatments, where soil amended with compost showed an increase in abundance. Pictures below are the more typical ciliate (Fig 11b) and a hypotricha (Fig 11a).

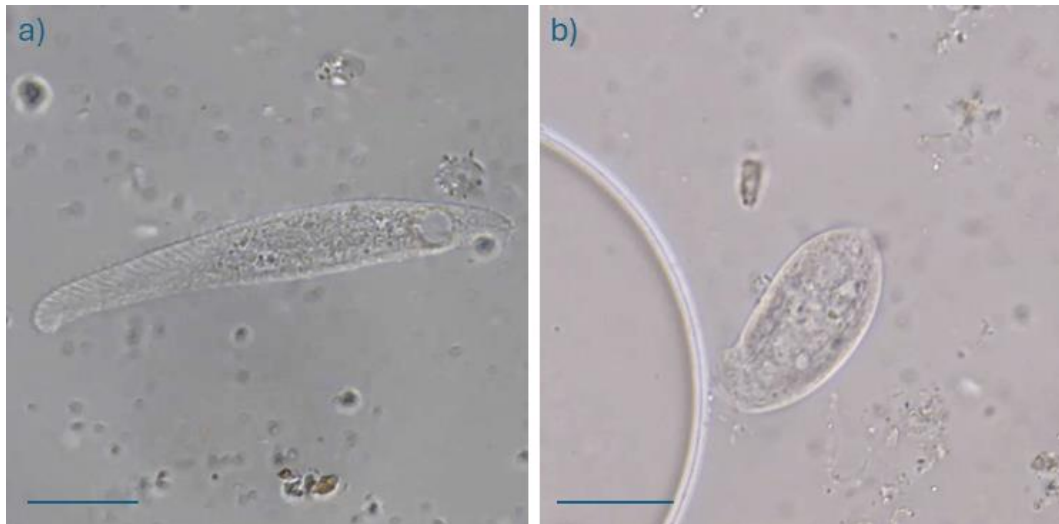


Figure 10: Examples of ciliates found in soil during a nine week cultivation of *Malus domestica* with two treatments Apple orchard soil (AOS) and Rest-product compost (RPC). The photos are taken inside of SoilChips, a microfluidic chip made of PDMS to replicate soil structures. A) *Hypotricha*, found in RPC5 at timepoint 3 B) Ciliate, found in AOS2 at timepoint 2. Blue bar for scale at 20 μ m.

Lastly are the more broad categories of taxa, hyphae of fungi (Fig 12a), heliozoa which can be counted under amoebazoid organisms (Fig 12b), diatoms which do not make up a phylogenetic group but are easily to morphologically group (Fig 12c) and lastly cysts (Fig 12d).

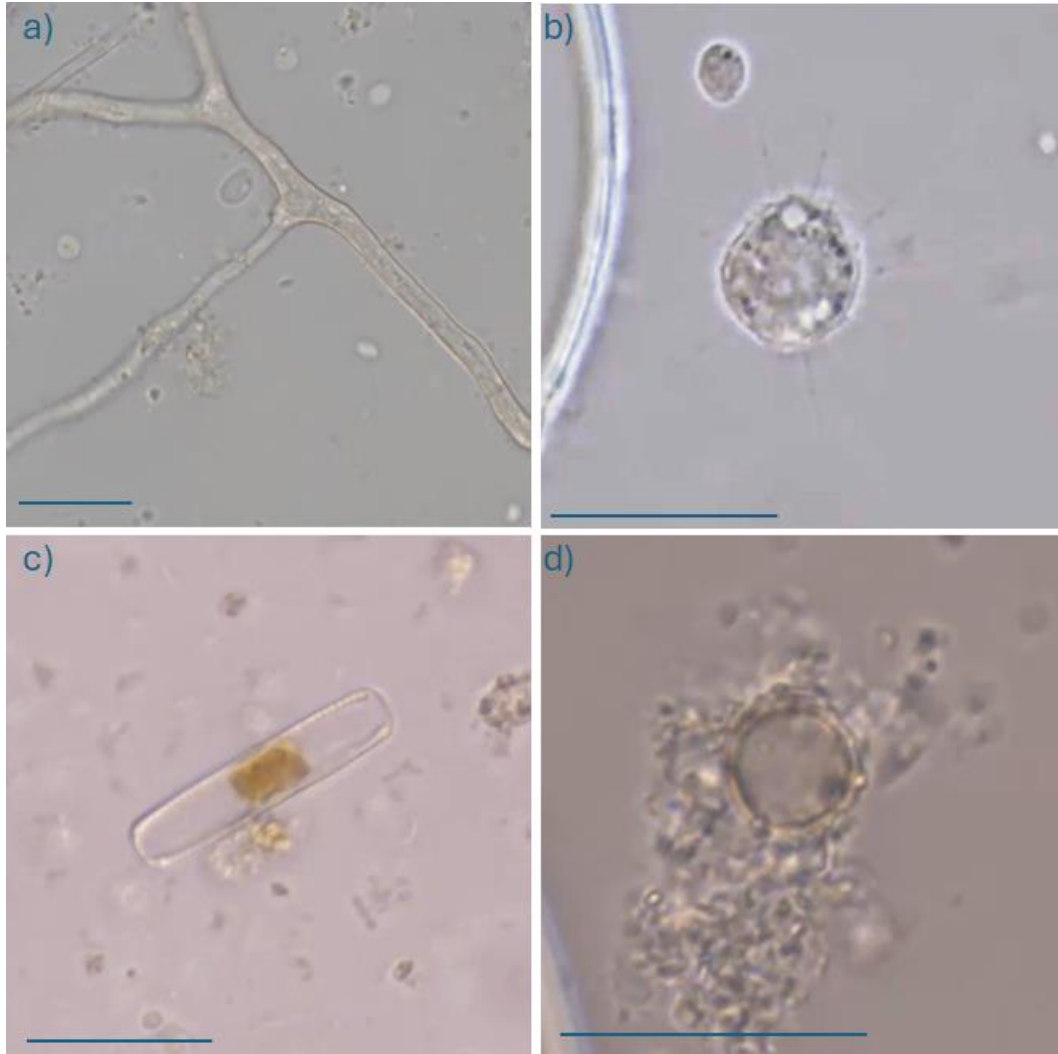


Figure 11: Other microbial groups found in soil during a nine week cultivation of *Malus domestica* with two treatments Apple orchard soil (AOS) and Rest-product compost (RPC). The photos are taken inside of SoilChips, a microfluidic chip made of PDMS to replicate soil structures. A) Hyphae, found in RPC1 at timepoint 2 b) Heliozoa, found in RPC5 at timepoint 2 c) Diatom, found in AOS5 at timepoint 3 d) Cysta, found in AOS4 at timepoint 2. Blue bar for scale at 20 μ m.

In both treatments, nematodes could be found (Fig 13).

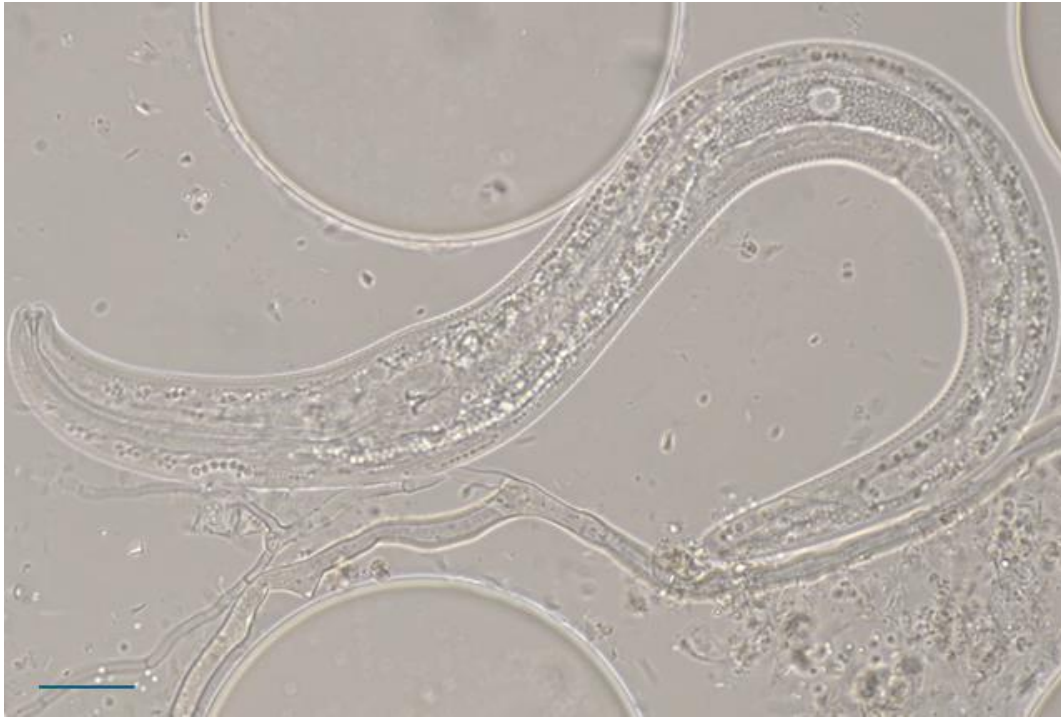


Figure 12: Nematode found in soil during a nine week cultivation of Malus domestica with two treatments Apple orchard soil (AOS) and Rest-product compost (RPC). The photo is taken inside of SoilChips, a microfluidic chip made of PDMS to replicate soil structures. Picture is taken in RPC3 at timepoint 3. Blue bar for scale at 20 μ m.

Other notable observations made in the soil was a ciliate dividing and become two during 3 minutes (Fig 14) and a hyphae growing 94,6 μ m during 9 minutes (Fig 15).

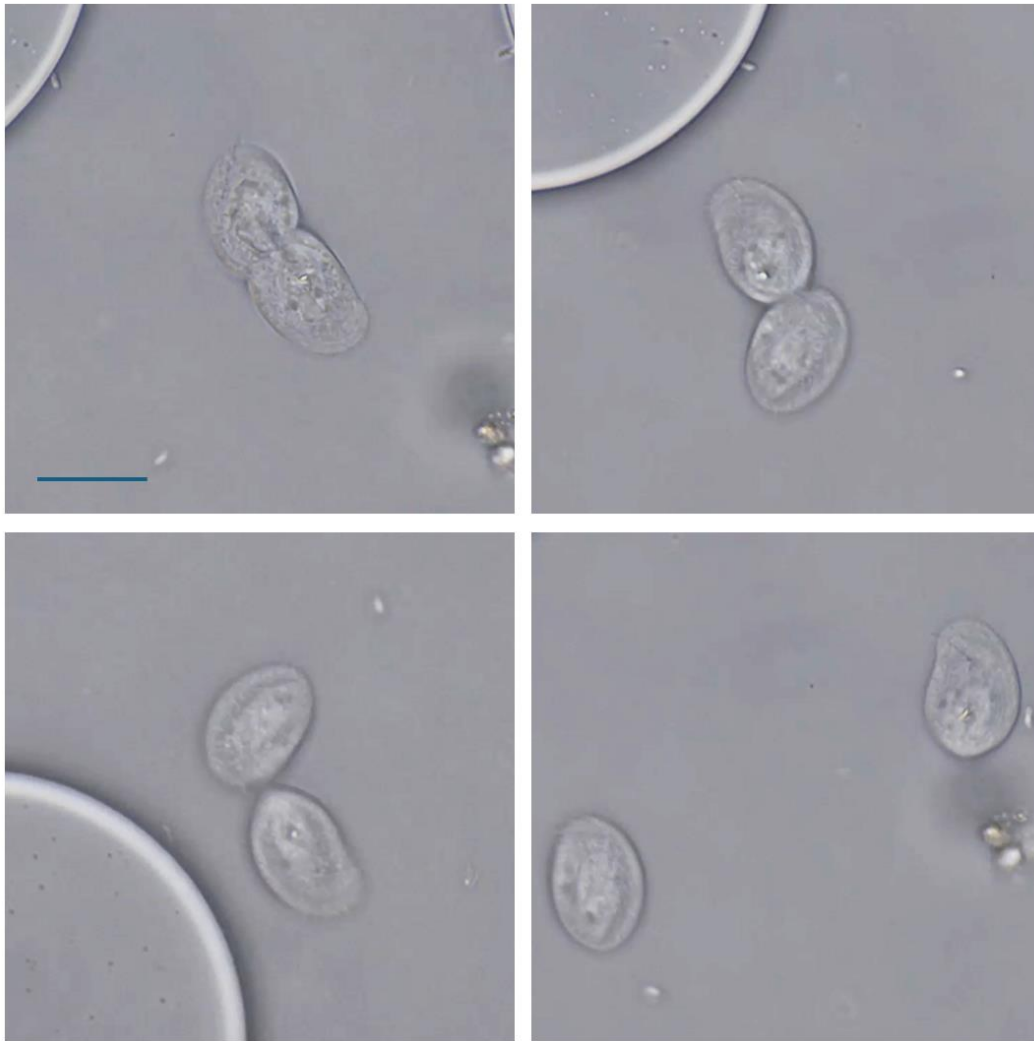


*Figure 13: A ciliate dividing and becoming two separate individuals. There is about 3 minutes between first and last picture in series. Observation was made in soil during a nine week cultivation of *Malus domestica* with two treatments Apple orchard soil (AOS) and Rest-product compost (RPC). The photo is taken inside of SoilChips, a microfluidic chip made of PDMS to replicate soil structures. Observation was done in treatment RPC2 at timepoint 1. Blue bar for scale at 20 μ m.*

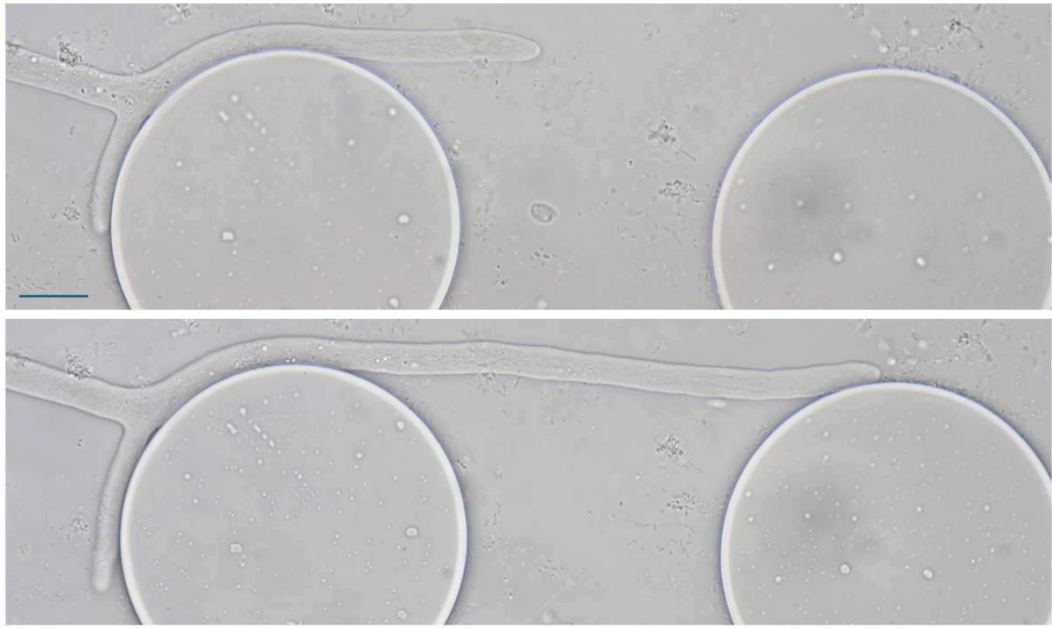


*Figure 14: Hyphae of fungi growing 94,6 μ m during 9 minutes. Observation made in soil during a nine week cultivation of *Malus domestica* with two treatments Apple orchard soil (AOS) and Rest-product compost (RPC). The photo is taken inside of SoilChips, a microfluidic chip made of PDMS to replicate soil structures. Observation made in RPC 5 at timepoint 1. Blue bar for scale at 20 μ m.*

4. Discussion

In this study, the primary objective was to evaluate the potential to implement circular economy principles in apple cultivation, specifically by improving soil health and productivity by using rest product compost. The compost was composed of apple waste, spent mushroom compost (SMC), and wood chips. To test the impact of using this rest product compost as a full basal fertilizer during cultivation a bioassay of apple branches was performed and the microbial population, growing parameters, soil physical parameters and nutrient analysis was taken into account for the final evaluation. The key hypotheses centered on the compost's ability to serve as a complete fertilizer over an 8 week period and promote greater microbial diversity and abundance compared to mineral-based fertilizers, and enhance soil structure by improving water holding capacity, porosity, and reducing bulk density relative to mineral fertilizer-based approaches.

4.1 Bioassay: Compost amendment and apple growth

Using rest product compost as investigated in this study can be determined to be successful, as proved by improved growth of apple branches. Not only did the compost fertilization treatment work as a basal fertilizer but also out-performed the mineral fertilizer significantly by increasing growth as related to shoot growth and leaf growth. This is further backed by multiple other studies showing increased yield and growth when plants have been treated with compost amendment (Schulz & Glaser 2012; Thompson et al. 2019; Altobaishi et al. 2023).

Interestingly, growth rate across treatments were similar but lasted longer in the RPC treatment before growth slowed down into the stationary phase of growth. The similarities in curves can be seen in Fig 5a; 5b.

Not only could an increased growth be seen in number of leaves and length of shoots, but also by increased leaf dry matter in compost treatment as compared to mineral fertilizer treatment.

Along with this, there was a significant difference between treatments in fresh weight of roots, stems and leaves. This signifies an increased water retention of compost treatment as there was no significant difference in dry matter between treatments as related to stems and roots. One reason for this could be due to the higher amounts of salt present in the compost treatment, and the increased water

retention could be a way to counteract the increased salt values. The salt stress was not big enough to damage the plants during the experiment, meaning that if the salt in the compost made the fresh weight increase, the salt was not the degree where it limited growth. However, salt tends to accumulate and it can take months or years in perennials until signs of salt stress can be seen (Ahmad & Anjum 2020).

Regarding growth, the branches used were of rootstock and no scion were grafted onto the branches as to avoid interference of uneven grafting. Since only the above-ground vegetative growth could be monitored continuously, a big part of plant growth that is the below ground root growth is not measured here. Only fresh- and dry weight of roots were calculated post-harvest but these measurements are not the whole picture. The clay-like orchard soil made it hard to keep every fine root and many were lost when removing the plants from the pots. Not only this, but since branches already had roots before planting, if measurements were available, it would still be hard to compare the results between treatments.

Overall, results are clear that the rest-product compost used for growing apple trees were successful.

4.2 Rest product compost as a fertilizer and soil improvement in circular apple production

4.2.1 Soil characteristics

Before cultivation, there was a significant difference in soil characteristics after compost amendment, but over the cultivation period, most of these decreased back to the original AOS pre-cultivation. This can be seen as a short-term boost of improved soil characteristics but as the plant and microbes develop, SOM is depleted. Other studies have reported short-term improved soil physical properties after addition of compost (Rivier et al. 2022; Vignozzi et al. 2023). The short-term effects of compost amendment can therefore be utilized further by continuous or multiple additions of compost to the growing orchards. This is also supported by the slow increase of SOM as well as soil fertility when applying compost continuously (Lucchetta et al. 2023).

The increased water holding capacity of the initial compost amended soil can also favour decrease need for irrigation.

4.2.2 Nutrient dynamics

The decreasing nutrient values can mainly be attributed to plant growth, but also nutrient cycling or assimilation by microbial population. Since Spurway-analysis measures the plant available nutrients, the results here do not give the full picture of what nutrients could be available further down the line. It is known that release

of nutrients from degrading SOM are slower and not nutrients that are available instantaneously, like with fast-release mineral fertilizer (Zhang et al. 2006). Reports have been made that re-application of compost to make best use of the potential release would be once every two years (Zhang et al. 2006). Along with rhizosphere priming, the potential release of the RPC soil could be greater than the potential release of the AOS soil after harvest.

As always when studying available nutrients, it is important to remember the complex patterns of availability and how different nutrient availability interacts with each other. High availability of one nutrient could limit availability of another, by different modes of binding, leaching, precipitation (Neilsen & Neilsen 2003). E.g., in a soil with high potassium and high calcium, there might be deficiency in magnesium even if levels should be sufficient.

As previously mentioned, experiments with compost as a fertilizer have reported salt stress of plants (Chaoui et al. 2003; Pittaway 2014). Here, interestingly, Sodium values went down after cultivation. This could be because of leaching, assimilation or calcium. Either way, since salt stress is a problem when using compost, it is positive to see the sodium levels as well as the EC going down.

Sulfur levels of apples are deemed low at under 100 ppm (Neilsen & Neilsen 2003). Here, the AOS levels are low with 31 mg/l (≈ 35 ppm), while RPC is sufficient with 390 mg/l (≈ 390 ppm).

The boron levels in both treatments are very low with under 1 mg/l, where 20-200 ppm would be sufficient.

While the calcium levels in the soil seem high, this is not unusual (Neilsen & Neilsen 2003). The high calcium values of the rest product compost is most probably because of the spent mushroom compost. To reach the right pH, limestone is often added to the substrate when growing mushrooms commercially (Zied et al. 2012). Since calcium and phosphorus bind to iron and precipitate, this could be the reason for the very low iron levels in the RPC treatment (Wajon et al. 1985). Supporting this is the increased iron supply after cultivation, when iron levels went down.

4.2.3 Microbial abundance over time

Before discussing microbial abundance, it needs to be stated that the abundance being described is not a determined absolute value but a value seen in the SoilChip and can before larger investigations regarding representativeness of the chip at hand solely be used for comparing between replicates and treatments. The space that was investigated in each chip was 0,1024 μ l (5,2cm * 200 μ m * 10 μ m). In addition, it is worth mentioning that microbial abundance was counted by hand and protist groups were determined by lay-man. However, distinct groups that are easily recognizable were determined before examination to limit false observations.

Interestingly, there was no significant differences between treatments in the bacteria. However, bacteria is a diverse group and with no ability to differentiate between groups and function of bacteria, this is hard to delve deeper into. Further, the high levels of bacteria in this experiment was problematic for the neural network. In pictures with high amounts of bacteria, not all could be in focus at the same time which led to many bacteria not being counted. Along with this, heavy soil debris led to many pictures being unusable for the neural network, making the sample size smaller and smaller. With this in mind, a new set of data would be needed to be sampled and reexamined to avoid wrongful conclusions. However, with a lack of time, this was not possible to do under the scope of this thesis.

The shifts in microbial community composition and abundance were in response to compost amendment. As expected, compost treated soil carried a larger microbial population. This is further backed by previous studies (Duong et al. 2013; Trupiano et al. 2017). The increased microbial abundance in the compost treated soil was highest at the beginning of cultivation, as expected.

How protists, microbiome and plants all work together is a understudied area. Since protists are hard to culture, it has long been hard to study their interactions. Using the soil chips, we can see them interact with plants and other microbes. While it is an understudied area, it has been reported that protozoa along with bacteria and hyphae can together benefit plants by their interactions (Krome et al. 2009; Koller et al. 2013; Weidner et al. 2017). The protozoa, usually bacteriovores, form the bacterial community in the rhizosphere. It has been shown that common amoeba can increase auxin-levels in the soil, favoring plant growth (Bonkowski & Brandt 2002; Krome et al. 2010).

4.3 Implications for soil health and management

In this comprehensive study of how the whole apple system change when adding compost, it is clear to see the positive impact of the compost. Not only is the rest-product compost more sustainable and locally made, it can also increase microbial abundance, improve soil physical characteristics and increase plant growth. With higher protist abundance, increased nutritional status and improvement of soil structure, there are many factors in the rest-product compost to attribute the increased plant growth to.

However, this experiment was performed in a time limited growing window and the reapplication rates and SOM depletion over time would still impact the commercial use of the compost over longer periods of time. Still, the success of this trail run proves the potential of using circular nutrient economy in apple cultivation.

To fine tune the compost application and implementation in a commercial orchard, further trials would need to be run.

While this specific composition of compost was successful as a basal fertilizer in a pot setting for two months, this would not be feasible on a larger scale because of limited fruit waste. This is further explored in Appendix 2, showing that only 20 ha could use this compost as a full basal fertilizer and that around 117kg of compost would need to be applied to each m², which of course is very unrealistic. This means that to have a successful circular economy using this composition of compost in a commercial orchard, another form of waste would need to be used, e.g. household food waste. However, this is not under the scope of this experiment but would need to be examined before wide spread use.

4.4 Conclusions

The increased growth of the apple trees amended with compost can be seen as a result of the increased microbial community and the structural changes to the soil characteristics along with increased SOM and increased nutritional status. The results of this thesis builds on previous studies and shows successful integration of rest-product compost amendment used as a full basal fertilizer of *Malus domestica*.

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Popular science summary

With a changing climate and intensification of pollution in the food production, improvements to sustainability is vital. In this study, we have shown that using compost using locally sourced rest-products can improve the soil health and apple growth as well as the microbial life in the soil.

Today, agriculture is maintained by using fertilizers and pesticides that cause intense pollution and harm to the environment. A lot of rest-products go to waste, losing valuable nutrients and causing eutrophication of surrounding land. This study proves that the reusing of these nutrients in composts can enhance soil health and improve apple tree growth as well as boost microbial life, all while also working as fertilizer. Without relying on chemical fertilizers, locally made composts can act as a stepping stone for farmers to implement more sustainable agricultural and horticultural practices.

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Appendix 1

Nitrogen contents and ECe vales were received from nutrient analysis from LMI, Helsingborg.

Pot		<i>Value</i>	<i>Unit</i>	Compost 6 N contents	<i>N-contents [mg/l]</i>	<i>ECe [mS/cm]</i>
Pot volume (V _p)		7,5	l	Rep 1	2,4	3,3
Pot radius (r)		12,5	cm ²	Rep 2	5,6	5,8
Pot surface area	$r^2 \cdot \pi \approx$	490,9	cm ²	Rep 3	2,8	4,2
Pot surface area (A _p)		4,9E-6	ha	Average [g/l] (N ₆)	0,0036	4,433333333
Nitrogen fertilization				Compost 5 N contents	<i>N-contents [mg/l]</i>	<i>ECe [mS/cm]</i>
Whole year (N)		30	kg/ha	Rep 1	15	5,7
8 weeks 30kg/ha	$N \cdot (56/365) \approx$	4,6	kg/ha	Rep 2	23	7
8 weeks 30kg/pot (N _{8 weeks})	$4,6 \cdot A_p \cdot 100 \approx$	0,023	g	Rep 3	7,1	9,9
				Average [g/l] (N ₅)	0,015033333	7,533333333

Volume compost per pot	<i>Calculations</i>	<i>Value</i>	<i>Ratio Compost:Soil in 7,5l pots</i>
Compost 6 (V ₆)	$N_{8 \text{ weeks}}/N_6 \approx$	6,3 l	80:20
Compost 5 (V ₅)	$N_{8 \text{ weeks}}/N_5 \approx$	1,5 l	20:80

EC of soil mixed with Compost in ratios of full fertilization

Let's assume that the soil of Kivik has ECe value of 1 mS/cm i ECe

EC of Compost 6 (80:20)	$(V_6/V_p) \cdot EC_{e6} \cdot (V_p - V_6)/V_p \cdot 1 \approx 3,9$
EC of Compost 5 (20:80)	$(V_5/V_p) \cdot EC_{e5} \cdot (V_p - V_5)/V_p \cdot 1 \approx 2,3$

Let's assume that the soil of Kivik has ECe value of 0,5 mS/cm

EC of Compost 6 (80:20)	$(V_6/V_p) \cdot EC_{e6} \cdot (V_p - V_6)/V_p \cdot 0,5 \approx 3,8$
EC of Compost 5 (20:80)	$(V_5/V_p) \cdot EC_{e5} \cdot (V_p - V_5)/V_p \cdot 0,5 \approx 1,9$

Soil salinity levels should generally be kept below 2dS/m, according to Boland A.M., Ziehri, A and Beaumont, J. 2002. *Guide to Best Practice in Water Management – Orchard Crops*

Based on nutrient and EC calculations, 20:80 (compost 5: apple orchard soil) was chosen.

Appendix 2

Waste before full yield (W_b)		18,00% (Olsson et al., 2015)
Waste after full yield (W_a)		2,00% (Olsson et al., 2015)
Yield Sweden 202x (Y)		25 000 000 kg (SBC, 2020)
Waste before full yield	$Y/((1-W_b)-Y)=$	5 487 805
Waste after full yield	$Y*W_a=$	500 000
Total waste (W_{tot})		5 987 805
N fertilizer contents compost 5 [g/l] (N_{c5})		0,0150
N fertilizer contents compost 6 [g/l] (N_{c6})		0,0036
Apple waste in compost 5		25%
Apple waste in compost 6		40%
Bulk density [g/l] (ρ_b)		590,7444
N fertilizer compost 5 [g/kg] (N_5)	$N_{c5}/(\rho_b/1000)=$	0,0254
N fertilizer compost 6 [g/kg] (N_6)	$N_{c6}/(\rho_b/1000)=$	0,0061
Area of orchards [ha] (A)		1 500 (SBC, 2018)
N fertilizer use [kg/ha/year] (N)		30
N fertilizer use [kg/year]	$A*N=$	45 000
Compost 5 weight for full fertilizer [kg] (m_5)	N fertilizer use/N fertilizer compost 5=	1 768 303 769
Compost 6 weight for full fertilizer [kg] (m_6)	N fertilizer use/N fertilizer compost 6=	7 384 305 556
*Note that compost will change in weight from first composted to mature compost		
Apple waste needed for full basal fertilization of all Swedish orchards if compost 5 is used (W_5)	$m_5*25%=$	442 075 942
Apple waste needed for full basal fertilization of all Swedish orchards if compost 6 is used (W_6)	$m_6*40%=$	2 953 722 222
Apple waste lacking for full basal fertilization of all Swedish orchards if compost 5 is used	$W_{tot} - W_5=$	-436 088 137

Apple waste lacking for full basal
fertilization of all Swedish orchards if
compost 6 is used

$$W_{\text{tot}} - W_6 = -2\,947\,734\,417$$

Realistic fertilizer area (all SWE waste)

$$\text{C5 [ha]} \quad (W_{\text{tot}}/25\%)/(N/(N_5/1000)) = 20,317114$$

$$\text{C6 [ha]} \quad (W_{\text{tot}}/40\%)/(N/(N_6/1000)) = 3,040809745$$

Conclusion: we do not produce enough waste but it does go a longer way to chose compost 5

$$\text{Area of orchard (X)} \quad X$$

$$\text{Yield [kg]} \quad Y/A * 1000 = 16\,666,67$$

$$\begin{aligned} \text{Apple waste produced in orchard X [kg]} & \quad Y/A * 1000 * W_a + Y/A * 1000 / ((1 - W_b) - \\ (W_x) & \quad Y/A * 1000) = 3\,991,87 \end{aligned}$$

$$\text{Apple bulk density [g/l] } (\rho_a) \quad 465$$

$$\text{Apple waste volume [l]} \quad W_x * (\rho_a / 1000) = 8\,582,52$$

$$\text{Compost 5 weight full fert.} \quad N / (N_5 / 1000) = 1\,178\,869,18$$

$$\text{Weight/m2 [kg/m2]} \quad (N / (N_5 / 1000)) / 10000 = 117,886918$$

$$\text{C5 volume [l]} \quad N / (\rho_b / 1000) = 1\,995\,565,41$$

$$\text{Apple waste needed [l] } (W_{\text{an}}) \quad 25\% * N / (\rho_b / 1000) = 498\,891,35$$

$$\begin{aligned} \text{\% of orchard that can be fertilized using} & \\ \text{compost 5} & \quad W_x / W_{\text{an}} \approx 1,7\% \end{aligned}$$

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