Effect of microplastics on soil pH, electrical conductivity, and plant growth

By
Manoj Krishna Guttula

Department of Bioresource Engineering

McGill University

Montreal, Quebec

June 2023

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science (Thesis)

Abstract

The use of plastic film mulch improves water use efficiency in horticultural crops and increases yields by retaining soil moisture, suppressing weeds, and increasing soil temperature. Over time, these plastics degrade to particles less than 5 mm in size (microplastics). There is concern that microplastics could be detrimental, but the effects of microplastics on soil properties and plant growth are not well understood. To bridge this knowledge gap, two experiments were conducted at the Macdonald Campus of McGill University to investigate the effects of two types of microplastics on soil properties and plant growth: low-density polyethylene (LDPE) and polylactide and polybutylene adipate-co-terephthalate (PLA+PBAT), at three concentrations (zero control, 0.5%, 1.0%, 1.5% w/w). In the first experiment, strawberries (*Fragaria* × *ananassa* cv. Albion) were grown in a greenhouse in clay loam field soil,following a fully randomized design with six replicates. The type and concentration of microplastics had a significant interaction effect on soil pH and electrical conductivity (EC) ($P < 0.05$). The treatment with 1.5% PLA+PBAT had a higher pH than all other treatments, while the treatment with 1.5% PLA+PBAT had lower EC than other all other treatments. In the second experiment, tomatoes (*Solanum Lycopersicon* cv. Rutgers) were grown in Agromix G6 media in a growth chamber following a randomized complete block design with five replicates. In this experiment, the pH of the 0.5% PLA+PBAT treatment was found to be significantly lower than that of the control group at the end of the experiment ($P < 0.05$). The apparent trends in pH and EC are consistent in both experiments. Additionally, the 0.5% PLA+PBAT treatment exhibited a significantly higher electrical conductivity (EC), compared to the 0.5% LDPE treatment ($P < 0.05$). Notably, the presence of microplastics did not significantly affect emergence rate, height, shoot biomass, or root biomass ($P > 0.05$). Plants grown in soil with PLA+PBAT had significantly more leaves and higher chlorophyll concentrations,as compared with LDPE and control treatments ($P < 0.05$). These differences invite further investigation into the underlying causal mechanisms. The potential effects of PLA+PBAT or similar polymers in the soil are interesting to growers, policymakers, and manufacturers of horticultural mulch films.

Keywords: Microplastics; Low-density polyethylene; Polylactide and polybutylene adipate-co-terephthalate; Horticultural plastic mulch; Strawberries; Tomatoes; Soil pH; Soil electrical conductivity; Emergence trial; Plant growth trial; Phytotoxicity

Résume

L'utilisation de paillis de film plastique améliore l'efficacité de l'utilisation de l'eau dans les cultures horticoles et augmente les rendements en retenant l'humidité du sol, en supprimant les mauvaises herbes et en augmentant la température du sol. Au fil du temps, ces plastiques se dégradent en particules de moins de 5 mm (microplastiques). On craint que les microplastiques puissent être nuisibles, mais les effets des microplastiques sur les propriétés du sol et la croissance des plantes ne sont pas bien compris. Pour combler ce manque de connaissances, deux expériences ont été menées au campus Macdonald de l'Université McGill pour étudier les effets de deux types de microplastiques sur les propriétés du sol et la croissance des plantes : le polyéthylène basse densité (PEBD) et le polylactide et le polybutylène adipate-co-téréphtalate (PLA+PBAT), à trois concentrations (témoin zéro, 0,5 %, 1,0 %, 1,5 % p/p). Dans la première expérience, des fraises (*Fragaria* × ananassa cv. Albion) ont été cultivées dans une serre dans un sol de limon argileux selon un schéma entièrement randomisé avec six répétitions. Le type et la concentration de microplastiques ont eu un effet d'interaction significatif sur le pH du sol et la conductivité électrique (CE) ($P<0.05$). Le traitement avec 1,5 % de PLA+PBAT avait un pH plus élevé que tous les autres traitements, tandis que le traitement avec 1,5 % de PLA+PBAT avait une CE plus faible que tous les autres traitements. Dans la deuxième expérience, des tomates (*Solanum lycopersicon* cv. Rutgers) ont été cultivées dans un milieu Agromix G6 dans une chambre de croissance selon un schéma en blocs complets randomisés avec cinq répétitions. Dans cette expérience, le pH du traitement PLA + PBAT à 0, 5% s'est avéré significativement inférieur à celui du groupe témoin à la fin de l'expérience ($P < 0, 05$). Les tendances apparentes du pH et de la CE sont cohérentes dans les deux expériences. De plus, le traitement PLA + PBAT à 0, 5% présentait une conductivité électrique (CE) significativement plus élevée par rapport au traitement LDPE à

0, 5% ($P < 0, 05$). Notamment, la présence de microplastiques n'a pas affecté de manière significative le taux d'émergence, la hauteur, la biomasse des pousses ou la biomasse des racines ($P > 0,05$). Les plantes cultivées dans le sol avec PLA + PBAT avaient significativement plus de feuilles et des concentrations de chlorophylle plus élevées par rapport au LDPE et aux traitements témoins ($P < 0,05$). Ces différences invitent à une enquête plus approfondie sur les mécanismes de causalité sous-jacents. Les effets potentiels du PLA+PBAT ou de polymères similaires dans le sol intéressent les producteurs, les décideurs et les fabricants de films de paillage horticole.

Mots-clés: Microplastiques ; Polyéthylène basse densité; Adipate-co-téréphtalate de polylactide et de polybutylène ; Paillis plastique horticole; Des fraises; Tomates; pH du sol ; Conductivité électrique du sol ; Essai d'émergence ; Essai de croissance des plantes ; Phytotoxicité

Acknowledgements

I am incredibly thankful to Dr. Grant Clark, my supervisor, and Associate Professor in the Department of Bioresource Engineering at McGill University. Despite his busy schedule, Dr. Clark provided invaluable input, compassionate assistance, and constructive feedback that had a significant impact on the outcome of my investigation. I would also like to express my gratitude to Dr. Yixiang Wang and Dr. Valerie Gravel from my Advisory Committee for their essential guidance and valuable ideas. Additionally, I want to extend my heartfelt appreciation to Research Associate Dr. Michael Boh for his exceptional guidance, unwavering support, insightful suggestions, and constant encouragement throughout my studies. Their collective assistance enabled me to successfully plan, execute, and conduct the trials at the research greenhouse and phytorium of the Department of Plant Science at McGill University, Macdonald Campus.

I would also like to thank the members of the EcoEng lab group for their cooperation and assistance with my work.

Furthermore, I would like to express my heartfelt gratitude to Dr. Vijaya Raghavan for his crucial guidance and emotional encouragement throughout my research. I am also grateful to Dr. Shiv Prasher and Dr. Chandra Madramootto for their assistance in providing laboratory materials and offering valuable insights during my study.

I sincerely thank Sarah-Ann Persechino, Serghei Dernovici, and Marc Samoisette for making the required space and materials available in the greenhouse, phytorium and Lods agronomy center.

I am greatly indebted to my friends Uday and Tejasvita for their encouragement, cooperation, and assistance my peers and colleagues provided throughout the investigations.

Above all, I am deeply grateful and honored to my dear parents, Sri Gopi Rao, and Smt. Durga Lakshmi, for their infinite affection and tireless efforts in creating my profession since my childhood. I'd also like to thank my family for consistently encouraging me during my studies.

I would like to offer my heartfelt appreciation to Dana Ingals, the Librarian, and the rest of the library staff for their unfailing cooperation.

Finally, I want to express my gratitude to McGill University for providing financial aid during my post-graduate studies.

Contribution of Authors

The candidate conducted the literature review and wrote the initial draft of the monograph thesis and received assistance and guidance from Dr. Osborne Grant Clark and Dr. Michael Yonga in editing and revising.

Table of Contents

List of Figures

List of Abbreviations

AWC	Available water capacity
EC	Electrical conductivity
ET	Evapotranspiration
ET_o	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FC	Field capacity
LDPE	Low-density polyethylene
MAD	Maximum Allowable Depletion
PBAT	Polybutylene adipate-co-terephthalate
PE	Polyethylene
PLA	Polylactic acid
PWP	Permanent wilting point
SAS	Statistical Analysis System
USDA	U.S. Department of Agriculture
w/w	Weight by weight (mass ratio)

1 Introduction

1.1. General Introduction

Plastic use in agriculture has numerous benefits for horticultural crop production. Plastic film mulch is commonly used to increase soil temperature, conserve water, reduce weed pressure and pest activity, enhance fertilizer efficiency, and boost crop yield and quality (Kasirajan & Ngouajio, 2012). However, plastic film mulch is believed to be one of the main sources of microplastics in agricultural and horticultural soils (Huang et al., 2020). These tiny particles, with a size of less than 5 mm, can accumulate in soils and might affect physical and chemical soil properties, nutrient cycling, food production, and food security. These risks call into question the suitability of plastic mulch film in the horticulture (Serrano-Ruiz et al., 2021).

Microplastics have infiltrated various ecosystems, including agricultural soils, urban areas, and even protected nature areas (Rochman, 2018). Their presence in soil is of concern because they might accumulate in food webs with unknown consequences and could even pose a threat to global food security (Zhang et al., 2020). Bläsing & Amelung (2018) stated that low-density polyethylene (LDPE) plastic film mulch and greenhouse coverings are the primary sources of microplastics in agricultural soils. LDPE film is anticipated to take over 300 years to decompose in the soil, and its residue can alter the soil's physical and chemical properties (Steinmetz et al., 2016). To tackle the potential problem of microplastic pollution in soil from conventional plastic films, like LDPE, biodegradable plastic films have been developed. They are considered to be environmentally friendlier than LDPE because they are presumed to completely degrade in natural environments, eliminating the need to remove them from the fields and deal with plastic debris (Bandopadhyay et al., 2018; Sintim et al., 2019). It is also presumed that conventional and biodegradable microplastics affect soil-plant systems differently. However, there are limited studies to corroborate these claims (Bandopadhyay et al., 2018; Li et al., 2014). A better understanding of the impact of microplastics on soil and plant health therefore requires further study.

1.2. Objective and Hypotheses of Studies

1.2.1. Broad Objective

This study investigates the impact of low-density polyethylene (LDPE) and polylactide and polybutylene adipate-co-terephthalate (PLA+PBAT) microplastics on soil chemical properties and plant growth.

1.2.2. Specific Objectives

1. To assess changes in pH and electrical conductivity (EC) in soil with different concentrations of LDPE and PLA+PBAT microplastics using strawberry as a model plant.
2. To assess changes in pH and electrical conductivity (EC) in growth media with different concentrations of LDPE and PLA+PBAT microplastics using tomato as a model plant.
3. To compare the growth of tomato plants (emergence, leaf number, height, chlorophyll content, shoot biomass, and root biomass) in the same experimental treatments as (2).

1.2.3. Hypotheses

1. The type of microplastics present in the soil influences soil chemical properties (e.g., pH, EC) using strawberry as a model plant.
2. The concentration of microplastics in the soil affects soil chemical properties (e.g., pH, EC) using strawberry as a model plant.

3. The type of microplastics present in the growth media influences soil chemical properties (e.g., pH, EC) and tomato plant growth (e.g., emergence of plants, average no. of leaves, average no. of leaflets, height, chlorophyll content, shoot biomass, root biomass).
4. The concentration of microplastics in the soil affects soil chemical properties (e.g., pH, EC) and tomato plant growth (e.g., emergence of plants, average no. of leaves, average no. of leaflets, height, chlorophyll content, shoot biomass, root biomass).

1.3. Scope

The study will show how LDPE and PLA+PBAT microplastics alter the pH and EC of the growing medium and affect plant growth. This research is relevant to greenhouse-grown strawberries in field soil and growth chamber-grown tomatoes in Agromix G6 media. Care and sound judgment is needed before applying the findings to other crops or environments because of the regulated environments they are subjected to.

2 Literature Review

2.1 Plastics in the Environment

The versatility, durability, and low production cost of plastic has made it indispensable. The durability of plastic enables to affect natural ecosystems for decades (Chamas et al., 2020). Since 1950, a total of 8.3 billion metric tons of plastic have been produced on a large scale (Geyer et al., 2017). By 2040, global plastic production is projected to reach 700 million tons, up from 367 million tons in 2020 (Plastics - the Facts, 2021). In 2016, 91 million tons of improperly managed plastic waste was produced globally from all sources, of which 11 million tons were discharged into marine ecosystems and 31 million tons into the terrestrial environment (The Pew Charitable Trusts and SYSTEMIQ, 2020).

Plastics are made from fossil-based (petroleum) and bio-based polymers. Bio-based means derived from biomass (plants) (European Bioplastics, 2016). Based on degradability, plastics are non-biodegradable or biodegradable. Nonbiodegradable plastics can be derived from fossil fuels or biomass. Biodegradable polymers are derived from either fossil or bio-based precursors. Biodegradability is linked to a material's chemical structure rather than its resource foundation. In other words, plastics made entirely from biobased materials might not be biodegradable, whereas plastics made entirely from fossil fuels might be (European Bioplastics, 2016). Plastics can be homopolymers (produced from a single monomer molecule, such as polyethylene, a long-chain ethylene polymer) or copolymers (formed from two or more polymers, such as starch and polycaprolactone).

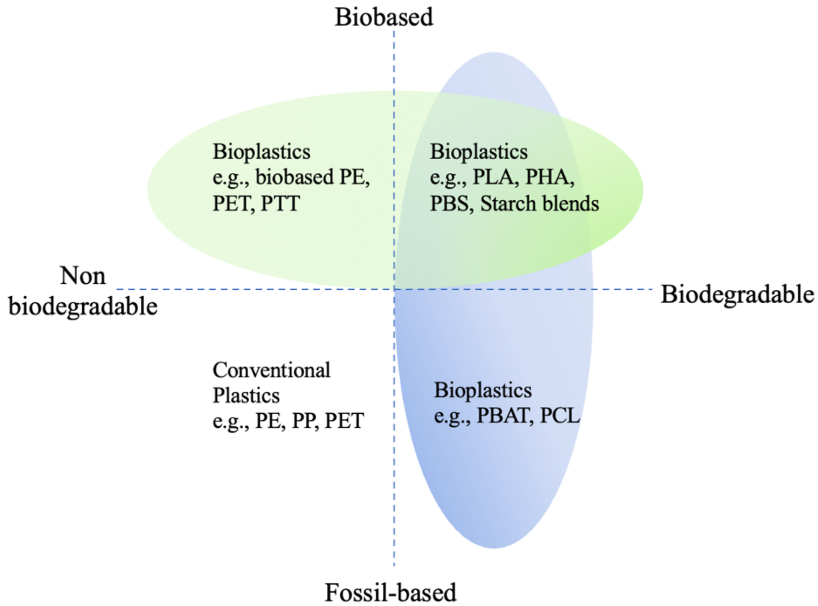

Figure 1: Material coordinate system of materials of plastics

Adapted from: European Bioplastics, 2016

2.2 Plastics in Agriculture

The agricultural industry heavily relies on plastic materials for plant and animal production. In the year 2019, the agricultural industry utilized a total of 12.5 million metric tons of plastic materials for plant and animal production globally (Food and Agriculture Organization of the United Nations, 2021). This extensive use of plastic highlights its crucial role in supporting modern agricultural practices. Furthermore, there is a projected increase globally in the utilization of greenhouse, mulching, and silage film, with an anticipated rise from 6.1 million tons in 2018 to 9.5 million tons by 2030 (Food and Agriculture Organization of the United Nations, 2021). These projections indicate the growing reliance on plastic materials in the agricultural sector. Moreover, Canada contributed significantly to this usage, producing 61,754 tons of agricultural plastic in 2020, with Quebec alone contributing 9,354 tons (Cleanfarms, 2021).

The development of plastic film technology revolutionized agricultural practices. In 1938, a British firm developed polyethylene sheet film technology to manufacture cheap greenhouses (Courter, 1965). Subsequently, in 1956, Professor Emery Emmert of the University of Kentucky pioneered the use of polyethylene film mulch, replacing cellulose acetate film mulch (Kasirajan & Ngouajio, 2012). This innovation, often attributed to Emmert, brought about significant benefits in agriculture. Low-density polyethylene (LDPE) plastic mulch became widely adopted due to its affordability, ease of production, durability, and flexibility (Kasirajan & Ngouajio, 2012). LDPE mulch positively impacted the agricultural microclimate, promoting plant growth, inhibiting weeds, improving nutrient use efficiency, minimizing erosion, and regulating soil temperature.

The extensive use of non-biodegradable LDPE mulch resulted in soil contamination, as recycling these plastic wastes proved costly and labor-intensive, leading to accumulation in agricultural fields and landfills (Kyrikou & Briassoulis, 2007). However, in response to the growing public concern about plastic pollution, there has been an increasing demand for biodegradable plastic film as an alternative (Brodhagen et al., 2017; Niaounakis, 2013). These biodegradable films are considered more environmentally friendly compared to LDPE because they can completely degrade in natural environments, eliminating the need for removal and dealing with plastic debris.

2.3 Microplastics

Microplastics are defined as plastic particles that have an average diameter of less than 5 mm (Hidalgo-Ruz et al., 2012). Microplastics are classified into primary and secondary microplastics based on their origin (Cole et al., 2011). Primary microplastics are manufactured, whereas secondary microplastics are generated by the degradation of larger plastic particles (Guo et al., 2020).

Microplastics can be categorized based on their physical properties, which include fibers, fragments, spheres, pellets, films, and foams (Issac & Kandasubramanian, 2021). Microplastic fibers are thin and flexible, with a uniform thickness along their length. Fragments are uneven in shape that ranges from round to angular. Spheres have smooth surfaces and are round. Pellets, also known as "nurdles," are larger than spheres, ranging in size from 3 to 5 mm. Films are flat, thin, and malleable, typically partially or completely transparent. Foams are soft, compressible cloud-like structures that are often white or opaque, but can also be colored (Rochman et al., 2019).

2.4 Microplastic Pollution in Soils

Microplastics have been studied in aquatic systems but less in terrestrial ecosystems. Microplastics have been found in various land ecosystems, including agricultural soils, urban environments, and protected wild regions (Dris et al., 2015; Scheurer & Bigalke, 2018). Concentrations vary widely depending on land usage and can reach higher levels than aquatic habitats. Microplastics can enter agricultural soils from non-agricultural sources such as wind-borne litter, atmospheric deposition, and irrigation (Dris et al., 2016). Weathering of LDPE plastic mulch and greenhouse covers is an important source of microplastics in agricultural soils (Bläsing & Amelung, 2018).

The average concentration of microplastics at an industrial location situated in Sydney, Australia, was found to be 67,500 mg kg^{-1} (Fuller & Gautam, 2016). The mean concentration of plastic particles in the riparian forest buffer zone at Dian Lake, Southwest China is 18,760 particles kg^{-1} (Zhang & Liu, 2018). The concentration of microplastic particles in various environments within the San Juan Cotzocón Municipality, located in the Gulf of Mexico Coastal Plain, including tropical rainforests, pine plantations, natural savannas, and pastures, ranged from 1.49 to 1.53 per gram of dry soil (Álvarez-Lopeztello et al., 2021). The concentration of film residue in agricultural soils located in Xinjiang, China, where plastic mulch is frequently utilized, exhibited a range of 0 to 502 kg ha^{-1} (mean 121.5 kg ha^{-1}), with the quantity strongly correlated with mulching years (Zhang et al., 2016). Blanco et al. (2018) reported that the amount of agricultural plastic waste from covering films in Italy's Barletta-Andria-Trani Province – Apulia region was 627 kg ha^{-1} every year.

2.5 Effects of Microplastics

Microplastics have significant effects on soil properties and microbial colonization. Microplastics have the ability to absorb and accumulate environmental pollutants, leading to alterations in the physical and chemical properties of soil. This includes changes in soil moisture, porosity, pH, and organic matter content (de Souza Machado et al., 2018). The presence of microplastics in the soil can impact microbial colonization and composition, which can have wide-ranging effects on soil structure and function (Wright et al., 2020). Changes in soil microbial composition can be challenging to predict, but they are known to influence nutrient cycling and other crucial soil processes (Rillig et. al., 2012). Microplastic pollution can result in a reduction in soil bulk density, which can negatively affect plant development due to increased evaporation rates (Wan et al., 2019). Additionally, soil-water relationships, such as water-holding capacity, can be influenced by microplastics (de Souza Machado et al. 2018). Different types of microplastics have been found to have varying effects on soil properties. For example, LDPE and starch-based biodegradable microplastics have been shown to raise pH and decrease electrical conductivity (EC) in agricultural soil (Qi et al., 2020; Palansooriya et al., 2022). Polyethylene microplastics, on the other hand, have been found to reduce soil bulk density (de Souza Machado et al. 2018).

Studies have demonstrated that the presence of microplastics can have detrimental effects on various aspects of plant development. For instance, the addition of biodegradable PLA microplastics in soil resulted in a reduction in shoot biomass and height of perennial ryegrass (Boots et al., 2019). Similarly, PLA microplastics inhibited the development of maize, including chlorophyll content and biomass, particularly at higher concentrations (10% w/w) (Wang et al., 2020). The type of microplastic used can also influence the effects on plant growth. For example, soybean plants treated with polyethylene microplastics exhibited less stem diameter compared to control and PE treatments at the flowering stage, while biodegradable microplastic treatments did not show significant differences throughout the plant's life (Li et al. 2021). The germination and shoot length of perennial ryegrass (*Lolium perenne*) were negatively impacted by the addition of PLA microplastics in a controlled pot experiment (Boots et al., 2019). Moreover, microplastic exposure, such as PE microplastics, has been found to decrease chlorophyll concentration, leading to reduced photosynthetic activity and growth in soybean plants (Li et al., 2023). However, the impact on chlorophyll content may vary depending on the plant species and the type of microplastic involved (Boots et al., 2019)

Microplastics influence the carbon cycle and nutrient levels in the soil. Microplastics play a role in the carbon cycle due to their carbon content. Materials like polystyrene or polyethylene, which are made up of approximately 80% carbon, can affect carbon sequestration and release in the soil. The presence of microplastics can influence soil microbial processes, rhizodeposition (the release of organic compounds by plant roots), and litter decomposition, which are important components of the carbon cycle (Rillig et al., 2021). Changes in microbial activity and composition can affect nutrient cycling and availability. Studies have shown that the addition of polypropylene microplastics to soil can significantly increase nitrogen levels, including soil nitrate-N and ammonium-N (Liu et al. 2017). This suggests that microplastics can have an impact on nutrient dynamics in the soil, potentially altering nutrient availability for plants and other organisms.

2.6 Growth Substrate for Potted Plants

The use of soilless substrates has emerged as a superior alternative to traditional field soil in the horticulture industry. Compared to field soil, soilless substrates offer enhanced control and consistency in providing an optimal growing medium for crops. They are carefully formulated to meet specific physical, chemical, and biological requirements, ensuring superior plant growth and productivity. By overcoming the limitations of field soil, soilless substrates have revolutionized container-based cultivation in greenhouse and nursery industries.

Extensive research has been conducted on soilless substrate mixes for container-grown crops since the 1950s when container-based cultivation was introduced in the greenhouse and nursery industries (Davidson et al., 2000). Initially, field soil, peat moss, and sand were commonly used, but certain crops showed poor growth in field soil and required sterilization of soil (Scott & Bearce, 1972).

Soilless substrates, such as peat, offer more consistency and homogeneity in quality compared to field soil (Bunt, 1988). Peat has favorable physical, chemical, and biological characteristics that promote plant growth, including high total porosity and low bulk density (Krucker et al., 2010). Coconut coir, derived from the mesocarp of the coconut fruit, has gained attention as a soilless substrate component in the greenhouse hydroponic vegetable production (Schmilewski, 2009). It has a higher pH value compared to peat. Non-organic materials like perlite and vermiculite are also used as soilless base materials. Perlite, a volcanic rock that expands when heated, provides increased porosity, air capacity, and shrinkage ratio when added at a volume of 25% to organic materials (Özer & Dede, 2018). Vermiculite, produced by inflating silicate material at high temperatures, enhances aeration and water and nutrient retention when used at 25-50% volume in soilless substrates (Nelson, 2003).

2.7 General Culture and Production of Strawberry

The strawberry (*Fragaria × ananassa*) is an important herbaceous perennial crop in Quebec. In 2021, the Food and Agriculture Organization (FAO) reported that the globe produced 9.17 Mt of strawberries. Canadians produced 27,250 tons of strawberries in 2022 (Government of Canada, 2023). Strawberries have been grown professionally in Quebec since the 1920s (Lamarre & Lareau, 1997). Quebec generated 60% of the strawberries' total national farm gate value in 2022 (Government of Canada, 2023).

Strawberry roots are shallow, with 50–90% in the upper 10-15 cm (Hancock et al., 2008). This crop needs sandy loam soil with moderately high (7–30%) organic matter, pH of 5.5-7.0, appropriate drainage, moderate irrigation and fertilization, sunny locations, and temperatures between 15 and 30°C (Hancock et al., 2008). Strawberry growth is hindered by temperatures above 35-40°C (Hellman & Travis, 1988).

The researchers at University of California created strawberry variety ‘Albion' from ‘Diamante' and ‘Cal94.16-1' in 1997 (Shaw & Larson, 2006). Albion is hardy in U.S. Department of Agriculture (USDA) North American hardiness zones 4a–7b (which encompasses several regions of Quebec) (Plant Hardiness Zones (2010). Albion is good at withstanding temperature swings and day-to-night changes, typical throughout Quebec production season (Orde et al., 2021). Albion has been demonstrated to yield high-quality fruits throughout the growing season regularly. The fruits are enormous, conical, darker, more complex, and sweeter than other day-neutral cultivars (Durner & Durner, 2018). Albion is more disease-resistant than its forebears.

Plant growth relies on nitrogen, phosphorus, and potassium. Nitrogen is a component of amino acids, which regulate all biological functions. A balanced nitrogen supply promotes leaf growth and a vibrant green color (Brady & Weil, 2008). Phosphorous increases photosynthesis, nitrogen fixation, blooming, fruiting, and maturity. Potassium helps roots grow and fight illness (Brady & Weil, 2008). Potassium also improves soil water absorption and leaf water loss. Plant growth also requires micronutrients or secondary elements. Magnesium, calcium, manganese, boron, and zinc are secondary elements. The recommended rate of nitrogen in fertilizer solution is 100 mg N/L (Cantliffe et al., 2007).

2.8 General Culture and Production of Tomato

Tomato (*Solanum lycopersicon* L.) is a dicotyledonous plant in the Solanaceae family that is widely cultivated. Tomato ranks second globally second in vegetable production in terms of yield, behind potatoes in the vegetables (Liu et al., 2022). It is recognized for its positive effect on health due to its high antioxidant content and minimal cholesterol, saturated fat, and sodium content (Cammarano et al., 2020; Capanoglu et al., 2010). Tomatoes can be grown in the field, but greenhouse cultivation is gaining popularity in North America because of higher yield and low pest infestation (Cook & Calvin, 2005). Tomatoes take 3.5–4 months to grow: 6–8 weeks from sowing the seeds to flowering and 7-8 weeks from blooming to ripening (Blancard, 2012). The ideal mean temperature for growth is between 18 and 25°C during the day and between 10 and 25°C during the night (Shamshiri et al., 2018). The ideal relative humidity for growth is between 65 and 75% (Bakker, 1991). Tomatoes thrive on well-drained, light, loamy soil with a pH between 5 and 7 (Papadopoulos & Tan, 1991).

Depending on the daily evapotranspiration (ET), the total crop water requirement ranges between 400 to 600 mm (Ronga et al., 2019). The crop factor (K_c) is used together with the reference evapotranspiration (ET_o) to determine how much water a crop needs at different stages of growth. For the initial stage, 0.4-0.5 mm/d (10-15 days), the vegetative growth stage, 0.7-0.8 mm/d (20-30 days), the flowering stage, 1.05-1.25 mm/d (30-40 days), the senescence stage, 0.8-0.9 mm/d (30-40 days), and the harvesting stage, 0.6-0.65 mm/d (10-15 days) (FAO, 2021).

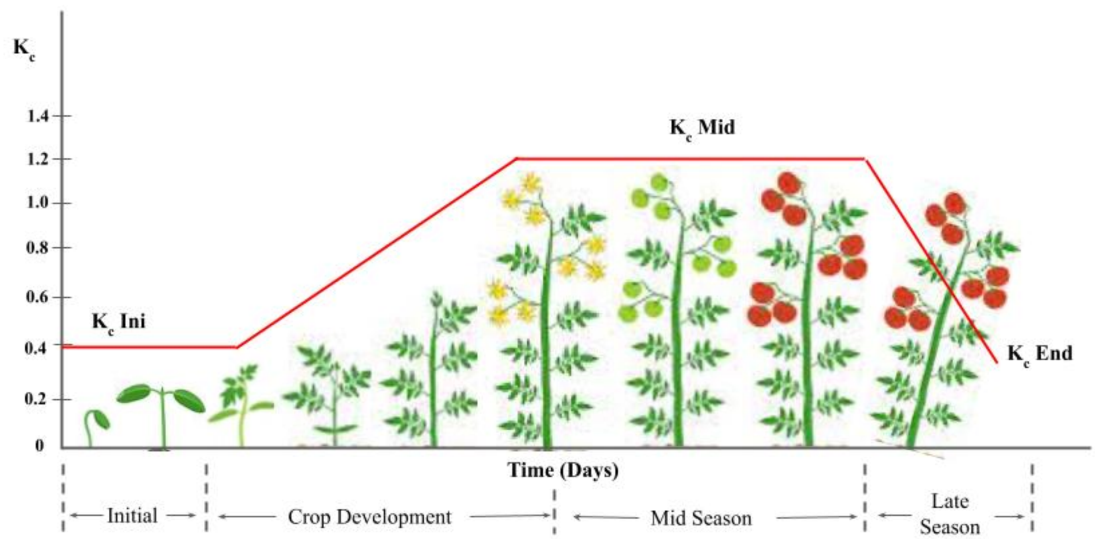

Figure 2: Crop coefficients at various stages of tomato crop growth

Adapted from: FAO, 2019

Inorganic fertilizers offer a key advantage over organic fertilizers: their nutrient-rich salts dissolve quickly, providing immediate and easily accessible nourishment to plants. This rapid solubility ensures that essential elements like nitrogen, phosphorus, and potassium are readily available for robust plant growth. The 4Rs (right source, right rate, right time, and right place) are crucial principles for effective fertilizer management, optimizing nutrient uptake and minimizing environmental impact (Johnston & Bruulsema, 2014). By adopting proper management approaches, farmers can tailor inorganic fertilizer applications to meet specific crop needs, considering soil conditions, plant requirements, and environmental factors. For high-yielding tomato types, recommended fertilizer ranges are 100-150 kg/ha N, 65-110 kg/ha P, and 160-240 kg/ha K ensuring optimal growth and productivity (FAO, 2020).

2.9 Irrigation Scheduling

Most farmers recognize the value of "on-time" irrigation, but the lack of real-time data makes irrigation scheduling (both in terms of quantity and timing) particularly difficult. The soil-based approach uses either soil water amount (volumetric or gravimetric measurements) or soil water activity (potential measurement) to aid in planning irrigation.

Soil Water Content

Soil water content (θ) refers to the quantity of water present within the soil (Novák & Hlaváčiková, 2019). From saturation (θ_{sat}) to the permanent wilting point (θ_{pwp}), it can be measured gravimetrically (g g^{-1}) or volumetrically (cm^3 cm^{-3}) (Novák & Hlaváčiková, 2019). Water fills all soil pores at saturated water content. The plant wilts permanently when it can no longer extract water. The θ_{pwp} occurs when soil matric potential (ψ_m) or pressure head reaches 1500 kPa (Rai et al., 2017). Plants can collect the most water when the water content is at field capacity (θ_{fc}). θ_{fc} occurs when the soil matric potential (ψ_m) or pressure head reaches 33 kPa (fig 4) (Datta et al., 2017).

The water-holding capacity of soil is directly linked to its surface area, specifically the specific surface area of soil particles (m^2/g). Clay soils, with their larger specific surface area compared to silt and sand, have the ability to hold more water (Sudan Acharya et al., 2014). Soil composition plays a significant role in determining the water content of soil. Soil surface moisture refers to the amount of water present on the surface of soil particles and is vital for irrigation scheduling, assessing plant stress, and determining crop output. Managing soil surface moisture levels is crucial for optimizing irrigation practices and promoting healthy crop growth.

Total Available Water

Soil available water capacity (AWC) is equal to field capacity (FC) minus the permanent wilting point (PWP) (Seneviratne et al., 2010). Above field capacity, soil pores lose water to gravitational drainage. The soil matrix tightly holds water below the wilting point, making it unavailable to plant roots (Seneviratne et al., 2010).

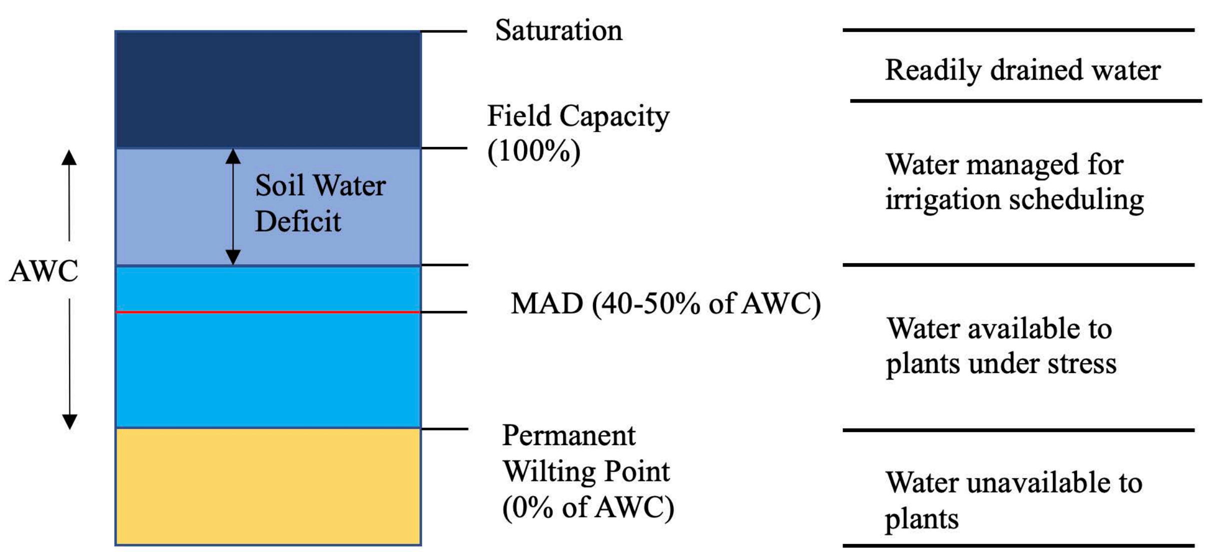

Figure 3:Soil water components

AWC: Available Water Content

MAD:Maximum Allowable Depletion

Adapted from: Howell & Meron, 2007

2.10 Literature review summary

This literature review provides an overview of various topics related to microplastics and their impact on agricultural soils. It begins by highlighting the substantial production and improper management of plastic waste, resulting in its accumulation in terrestrial ecosystems. The review then discusses the use of plastics in agriculture, specifically mulch films, and the growing demand for biodegradable alternatives. It further explores the concept of microplastics, including their classification, sources, and presence in different land ecosystems. The review also examined the effects of microplastics on soil properties and plant development. Additionally, it explores the use of soilless substrates as a growth medium for potted plants, emphasizing their advantages over traditional field soil. Based on this literature review, it is still unclear about the effect of microplastics in agricultural soils on soil properties and plant growth we therefore conducted the experiments using strawberries and tomatoes as described in the following sections.

3 Materials and Methods

3.1 Preparation of Microplastics

LDPE mulch film (1 mil thickness, CLIMAGRO, Saint-Laurent, QC) and PLA+PBAT mulch film (1 mil thickness, FilmOrganic, Laval, QC) were folded and cut into squares of approximately 1 × 1 cm and 3 × 3 cm, respectively. The squares of plastic film were placed, about 8 g at a time, inside a stainless-steel spice grinder (DE-Z1112V-CX-155, Homend, Duluth, GA) and ground four times, for two minutes each time, with five-minute cooling periods. The output of five batches was bulked and ground for 6 minutes, following the same intervals mentioned above. The particles were sieved through 4.75-mm and 0.50 mm screens, and the middle size fraction was retained to obtain microplastics in the range commonly reported in the literature (Zhang & Liu, 2018). All batches of microplastics of each type were placed in a glass bowl, and mixed thoroughly to homogenize them, and the mass required for each experimental unit (pot) was then weighed and stored in separate glass jars until use.

Figure 4: Microplastic preparation from plastic mulch sheet

3.2 Strawberry Experiment

3.2.1 Experimental Site

The experiment was conducted in the research greenhouse complex located at the Macdonald Campus of McGill University, Sainte Anne de Bellevue, Quebec (Lat. 45°24’ N; long. 73°56’ W) for eight weeks from May 8th to July 8th, 2022. The 8-week period allowed for plant monitoring from the transplant stage to plant maturity at six weeks, plus two extra weeks during production to investigate the effects of microplastics at various stages of strawberry growth.

3.2.2 Environmental Conditions

Plants were cultivated in this experiment under natural light supplemented by high-pressure sodium (HPS) lamps with a photosynthetic photon flux density (PPFD) of 200 mol m^{-2} s^{-1} at the plant level and a daily photoperiod of 16 hours of light and 8 hours of darkness. The day and night temperatures were around 25-32°C and 20-25°C, respectively. Relative humidity was regulated between 70 and 80%.

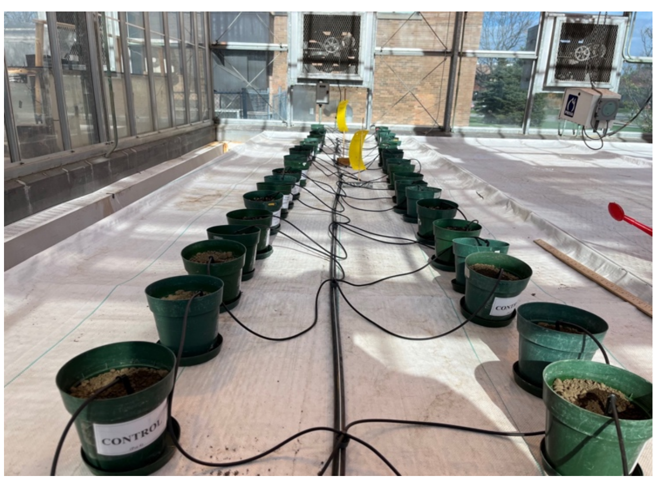

Figure 5: Growth bench with completely randomized experimental setup and drip irrigation.

3.2.3 Preparation of Experimental Soil

The soil was collected from an agricultural field's root zone (0 – 20 cm depth) at the Emile A. Lods agronomy research center of McGill University, Sainte Anne de Bellevue, Quebec (Lat 45°26' N; long. 73°55' W; 39 m above MSL). Clayey loam soil with a field bulk density of 11.17 g cm-3 and moisture content of 0.113 m3 m-3 was used. Collected soil was spread on the concrete floor and homogenized with a shovel using a cone and quartering method (Schumacher et al., 1990). During this process, roots and rocks were removed from the bulk soil. The homogenized soil was transported to the Ecological Engineering Research Laboratory of McGill University in paper bags and stored at room temperature for 72 hours before use.

3.2.4 Treatment Details

A control soil was created without microplastics. The treatment soils were made by mixing LDPE and PLA +PBAT microplastic particles in 0.5% w/w, 1% w/w, and 1.5% w/w of homogenized air-dried soil. The control treatment (treatment 1) had 1500 g of soil, while treatment 2 had 1492.5 g of soil and 7.5 g of LDPE microplastics, treatment 3 had 1485 g of soil and 15 g of LDPE microplastics, treatment 4 had 1477.5 g of soil and 22.5 g of LDPE microplastics, treatment 5 had 1492.5 g of soil and 7.5 g of PLA+PBAT microplastics, treatment 6 had 1485 g of soil and 15 g of PLA+PBAT microplastics, treatment 7 had 1477.5 g of soil and 22.5 g of PLA+PBAT microplastics.

3.2.5 Soil Moisture Estimation

Gravimetric Method: The procedure begins with collecting and weighing field samples of soil. Then the soil was oven dried at a temperature range of 100-110ºC for 24 hours. Recording the change in weight of soil per unit weight of oven-dried soil gives the gravimetric soil water

content.

This process is accurate but is time-consuming and not practical for continuous measurement. The gravimetric water content (wcm) can be converted to volumetric water content by multiplying it with the soil's bulk density.

$$\textbf{\textit{Gravimetric soil water content (g g}}^{\boldsymbol{-1}}\textbf{\textit{)}} = \frac{Weight\ of\ moist\ soil - weight\ of\ oven\ dry\ soil}{weight\ of\ oven\ dry\ soil} \qquad \textit{Equation 1}$$

$$\textbf{\textit{Volumetric soil water content (cm}}^{\boldsymbol{3}}\textbf{\textit{cm}}^{\boldsymbol{-3}}\textbf{\textit{)}} = \frac{Volume\ of\ water}{Volume\ of\ oven\ dried\ soil} \qquad \textit{Equation 2}$$

3.2.6 Potting

Bench tops were cleaned and disinfected with a bleach solution (0.6% v/v NaOCl). A plastic sheet was placed over the bench. Prepared soils were homogeneously mixed with each of the two microplastic types according to predetermined concentrations of 0.5%, 1.0%, and 1.5% w/w per treatment. The selected concentrations have been reported in some soils (Corradini et al., 2021; de Souza Machado et al., 2018; Qi et al., 2020). Treated soils were added to 2.78 L polypropylene pots (Height = 18.5 cm, bottom diameter = 14 cm, top diameter = 16.2 cm).

The pots were placed on a bench in the greenhouse, following a completely randomized design. The pots were additionally randomized each week to compensate for boundary effects. Initial gravimetric moisture content in the microplastic-treated soils and control was uniformly set at 0.18 m^3m^{-3} by adding 70 ml of water per pot.

3.2.7 Planting Species

A day-neutral variety of strawberry (*Fragaria* × *ananassa* cv. Albion) bare root transplants were obtained from a commercial supplier, Lareault Nurseries, Quebec, Canada, and stored in refrigeration at 4° C for four weeks before transplanting. During storage, bare root transplants were moistened by spraying tap water to prevent them from drying up (Lieten et al., 2005) before transplanting. Bare root strawberry transplants were planted in each pot 30 days after refrigeration on May 8, 2022.

3.2.8 Crop Irrigation and Fertigation

A drip irrigation system, outfitting a single drip emitter to each pot on the greenhouse bench, was installed for irrigation and fertigation. Tap water was used for irrigation, and deionized water for fertigation. The main line had an operating pressure of 137.9 kPa and was equipped with a 10 mm Polyvinyl Chloride (PVC) pipe, while the lateral was connected using a 5 mm PVC pipe. The drip emitters had a flow rate of 18.5 ml min^{-1} pot^{-1}. Plants were initially irrigated five times daily with 80 ml for two minutes to promote initial root growth. Following that, irrigation frequency and duration were changed to 150 ml starting on day 15 to satisfy plant water requirements.

The fertilizer requirements of each treatment were calculated based on 2.0 kilograms of soil per pot and supplied through the drip irrigation system. The recommended rate of 100 mg N/L was applied through a standard water-soluble 20-20-20 nutrient solution, made by dissolving 250 g of MiracleGro fertilizer in 5 L of water. The injector was set for a 1:100 fertilizer/water dilution. Daily drip and drain nutrient solutions measurements were monitored and adjusted within the range of pH 5.5±1 pH and EC1.5±0.2 mS cm^{-1} EC, necessary to keep the plants healthy (McKean et al., 2020).

3.2.9 Data Collection

3.2.9.1 pH and EC Measurements

During the experiment, pH and EC measurements were taken using a handheld soil pH meter (HI99121, Hanna Instruments, Smithfield, Rhode Island) and a direct soil EC tester (HI98331, Hanna Instruments, Smithfield, Rhode Island), respectively, on days 30, 37, 45, and 60.

3.2.10 Experimental Design

The experimental design was a six-replicate complete randomized design with two microplastic types (i.e., LDPE and PLA+PBAT) and three concentrations in the soil (i.e., 0.5%, 1.0%, and 1.5% w/w) along with a control. Seven experimental treatments were in total, including a control treatment, which did not receive any microplastics. The treatments were 0.5% w/w low-density polyethylene microplastics, 1% w/w low-density polyethylene microplastics, and 1.5% w/w low-density polyethylene microplastics, 0.5% w/w PLA +PBAT microplastics, 1% w/w PLA +PBAT microplastics, and 1.5% w/w PLA +PBAT microplastics. The seven experimental treatments were replicated six times. Forty-two experimental units were randomly placed in 21 rows and two columns. Each experimental pot has a spacing of 6 cm, with a two-meter gap between each column on a 550 X 165 cm bench in the greenhouse.

3.3 Tomato Experiment

3.3.1 Experimental Site

The experiment was conducted in pots in the growth chamber located at the Macdonald Campus of McGill University, Sainte Anne de Bellevue, Quebec (Lat. 45°24’ N; long. 73°56’ W) for eight weeks from November 4th to December 31st, 2022.

3.3.2 Environmental Conditions

In this experiment, plants are cultivated in a Conviron reach-in growing chamber outfitted with 12 incandescent bulbs and 16 fluorescent tubes. The lighting was set to a photosynthetic photon flux density of 450 µmol m^{-2} s^{-1} during the 16 hours photoperiod. The temperature was set to 22°C during the day and 18°C at night, and relative humidity was set to 70%.

Figure 6:Tomato plants in a Conviron growth chamber arranged in a completely randomized block design.

3.3.3 Preparation of Experimental Soil

Agromix® G6 (Fafard et Frères, Ltd., Saint-Bonaventure, Quebec) is a commercial soilless substrate that is recommended for most potted plants. The 300 g of substrate was hydrated with 90 ml of water for to maintain the media's moisture level at 50% water holding capacity before sowing the seeds.

3.3.4 Treatment Details

A control growth media was created without microplastics. The treatment soils were made by mixing LDPE and PLA +PBAT microplastic particles. Each pot in control /treatment 1 contained 300 g of soil, while treatment 2 contained 300 g of soil and 1.5 g of LDPE microplastics, treatment 3 contained 300 g of soil and 3 g of LDPE microplastics, treatment 4 contained 300 g of soil and 4.5 g of LDPE microplastics, treatment 5 contained 300 g of soil and 1.5 g of PLA+PBAT microplastics, treatment 6 contained 300 g of soil and 3 g of PLA+PBAT microplastics, treatment 7 contained 300 g of soil and 4.5 g of PLA+PBAT microplastics.

3.3.5 Potting

Prepared soils were homogeneously mixed with each of the two microplastic types according to predetermined concentrations of 0.5%, 1%, and 1.5% on a dry weight basis per treatment. The selected concentrations have been reported in some soils (Corradini et al., 2021; de Souza Machado et al., 2018; Qi et al., 2020). The mixture for each replicate was placed into a 2-L polypropylene plant pot (experimental unit) (Height = 15 cm, bottom diameter = 10 cm, top diameter = 15 cm (KORD Products, Toronto) and were filled with moist horticultural Perlite growth medium (Fafard et Frères, Ltd., Saint-Bonaventure, Quebec).

The pots were placed on a 64 × 166 cm bench in a growth chamber (GEN 2000, Conviron, Winnipeg, MB), spaced 3 cm apart and arranged in nine rows and four columns, following a completely randomized block design to compensate for edge effects.

3.3.6 Planting Species

Ten tomato seeds (*Solanum lycopersicon* cv. Rutgers, Pépinière Cramer Inc., Île-Perrot, QC) were sown in each pot. Each treatment was replicated five times for a total of 35 pots. An additional pot was placed in the growth chamber, without microplastics, to monitor the EC of drainage water. The pots were numbered from 1 to 36.

3.3.7 Crop Irrigation and Fertigation

The amount of water draining out may be used to manage irrigation in soilless media (also referred to as overdrain or percentage leach). Some overwatering is required, especially in greenhouse drip irrigation systems, to adjust for irrigation system inconsistency, plant-to-plant variances, and location differences (Heuvelink, 2005).

Initially, each pot was manually irrigated daily with 100 ml of tap water, resulting in about a 15% overwatering rate, as verified by monitoring the amount of water draining from the extra pot. On day 21, the quantity of water was changed to 300 ml (Harmanto et al. 2005). The pots were fertigated three times a week using a standard water-soluble 20-20-20 nutrient solution (MiracleGro, Scotts Canada Ltd., Mississauga, ON). The nitrogen (N) concentration in the fertigation solution was 50 mg/L from day 7–15, 75 mg/L from day 16–25, 125 mg/L from day 26–45, and 175 mg/L from day 46–60 (Rutledge, 2015). The EC was monitored to maintain optimal plant growth conditions. Drainage water was collected in Falcon tubes from the saucer under the extra pot and three pots picked at random, using a random number generator. EC was measured to verify that it remained under 2.0 dS/m (Rutledge, 2015). The water was then returned to the saucer from which it was collected.

3.3.8 Data Collection

3.3.8.1 pH and EC Measurements

During the experiment, pH and EC measurements were taken using a handheld soil pH meter (HI99121, Hanna Instruments, Smithfield, Rhode Island) and a direct soil EC tester (HI98331, Hanna Instruments, Smithfield, Rhode Island), respectively, on days 30, 37, 45 and 60.

3.3.8.2 Emergence Percentage

The emergence rate was determined as the percentage of seeds that had sprouted 21 days after 50% of the control plants appeared (day 30) (Environmental Protection Agency, 2012). All fully grown leaves per plant were counted at the end of the emergence period. A leaf is fully developed when the petiole is visible outward from the axil. The number of plants in each pot was then reduced to two seedlings with the highest number of developed leaves.

3.3.8.3 Number of Leaves

The number of leaves was determined by averaging the number of fully developed leaves per plant per replicate on days 30, 37, 45, and 60.

3.3.8.4 Plant Height Measurement

During the experiment, tomato plants' height was recorded on days 30, 37, 45 and 60. Each plant's height was measured using a ruler from the soil surface to the apex of its longest leaf.

3.3.8.5 Leaf Chlorophyll Content

A SPAD-502 (Konica Minolta, Osaka, Japan) sensor was used to measure chlorophyll levels in the leaves. Measurements were taken on days 30, 37, 45, and 60 from the two youngest, completely formed leaves on each plant. Three leaflets per leaf were measured, beginning with the apical leaflet and progressing toward the mainstem (Gianquinto et al., 2006). The mean SPAD value was calculated for the 12 leaflets measured from each pot (Soval-Villa et al., 2002).

3.3.8.6 Shoot Biomass

The shoot biomass of the tomato seedlings was assessed on three different days: day 30, day 45, and day 60. On day 30, the shoot biomass was determined by using the culled seedlings, while leaving two seedlings in each pot. On day 45, one of the two remaining plants in each pot was removed, and on day 60, the last plant was culled. To assess the shoot biomass, the above-ground section of the seedlings was cut at the soil surface. The cut shoots from each pot were then weighed (MS4002S, Mettler Toledo, Greifensee, Switzerland) and dried in an oven at 60°C until they reached a constant weight. Subsequently, they were weighed again to determine their dry mass. Based on these measurements, the average dry biomass per plant was calculated for each pot (Guo et al., 2021).

3.3.8.7 Root Biomass

On the last day, root biomass was measured by carefully removing soil without disturbing the roots. A brush was used to remove excess soil. Roots were weighed (MS4002S, Mettler Toledo, Greifensee, Switzerland), dried in an oven at 60°C until their weight was constant and then weighed again to determine their dry mass (Guo et al., 2021).

3.3.9 Experimental Design

The experimental design was a complete random block design with five replicates. Thirty-five experimental units were randomly assigned to positions in the growth chamber arranged in nine rows and four columns. For statistical purposes, they were divided into 5 blocks. The blocking was the test for edge effects. Each experimental pot was spaced 3 cm apart on a 64 ×166 cm platform in the growth chamber.

3.4 Statistical Design

Data were analyzed using *Proc GLM* of the SAS statistical software version 9.4 (SAS Institute Inc., Cary, NC). Proc Univariate was used to check the normality of the data. The data were subjected to analysis of variance (ANOVA) ($P \leq 0.05$) to test the significance of the effects of different treatments on plant growth and soil properties. Microplastic type, concentration, and time (day of measurements) were fixed effects. Growth medium pH, EC, number of tomato leaves, and SPAD chlorophyll content were dependent variables. The Tukey-Kramer posthoc test was used to test for significant differences at $P < 0.05$ (Kim, 2015).

The blocking was found to be non-significant and was not included in the statistical model.

4 Results and Discussion

4.1 Results of the Strawberry Experiment

4.1.1 The Effect of Microplastics on the pH of Soil

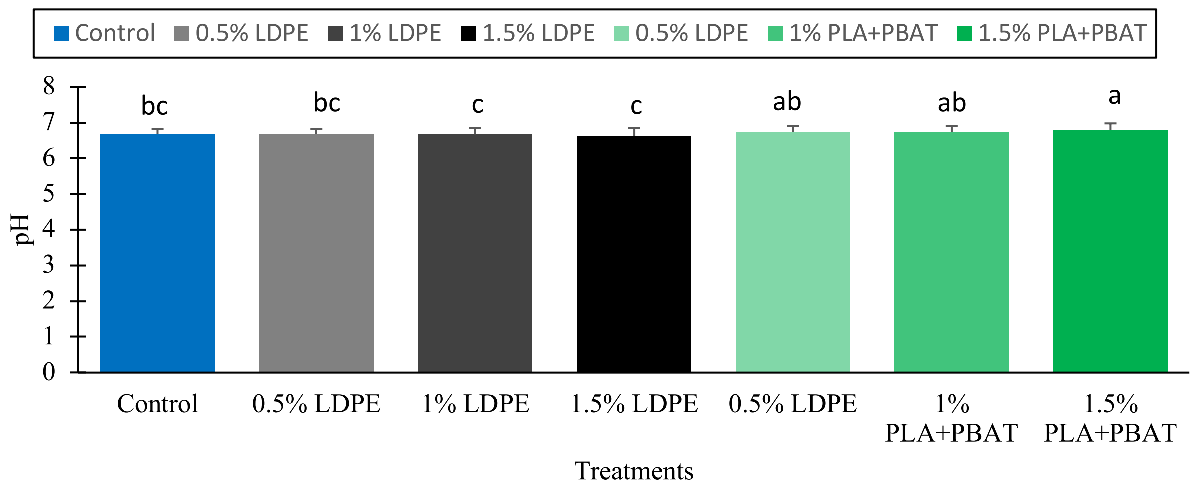

Figure 7: The impact of different concentrations of LDPE and PLA+PBAT microplastics on soil pH. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

The statistical analysis revealed that treatment groups saw significance between the interaction of the type and concentration, with P-values of <0.04 for each interaction. The application of PLA+PBAT at a concentration of 1.5% resulted in more soil pH compared to the control and LDPE treatments ($P < 0.05$). Furthermore, a growing trend towards pH was observed in the PLA+PBAT treatments as the microplastic concentrations increased. Specifically, the 1.5% treatments exhibited a higher pH compared to the 0.5% and 1% PLA+PBAT treatments. On the other hand, an inverse correlation was observed between the pH levels and the concentration of microplastics in the LDPE treatments. Specifically, the LDPE treatments with higher microplastic concentrations, such as the 1% and 1.5% treatments, exhibited lower pH levels compared to the LDPE treatment with a concentration of 0.5%.

4.1.2 The Effect of Microplastics on the EC of Soil

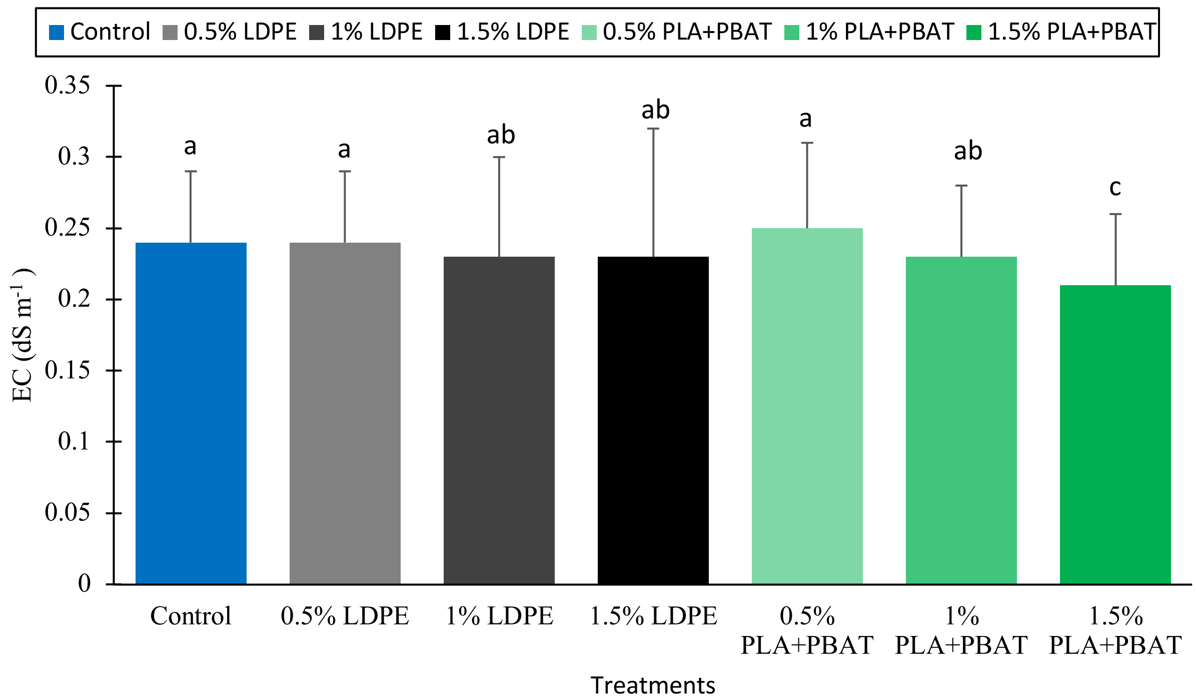

Figure 8: The impact of different concentrations of LDPE and PLA+PBAT microplastics on soil EC. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

The statistical analysis revealed that treatment groups saw significance between the interaction of the type and concentration, with P-values of <0.05 for each interaction. The application of PLA+PBAT at a concentration of 1.5% resulted in less soil EC compared to the control and LDPE treatments ($P < 0.05$). The electrical conductivity (EC) of the soil relatively decreased with increasing concentrations of both types. The PLA+PBAT treatments showed a trend toward lower EC values with increasing microplastic concentrations; the 0.5% and 1% treatments had higher EC values than the 1.5% treatment.

4.2 Results of the Tomato Experiment

4.2.1 The Effect of Microplastics on the pH of the Soil

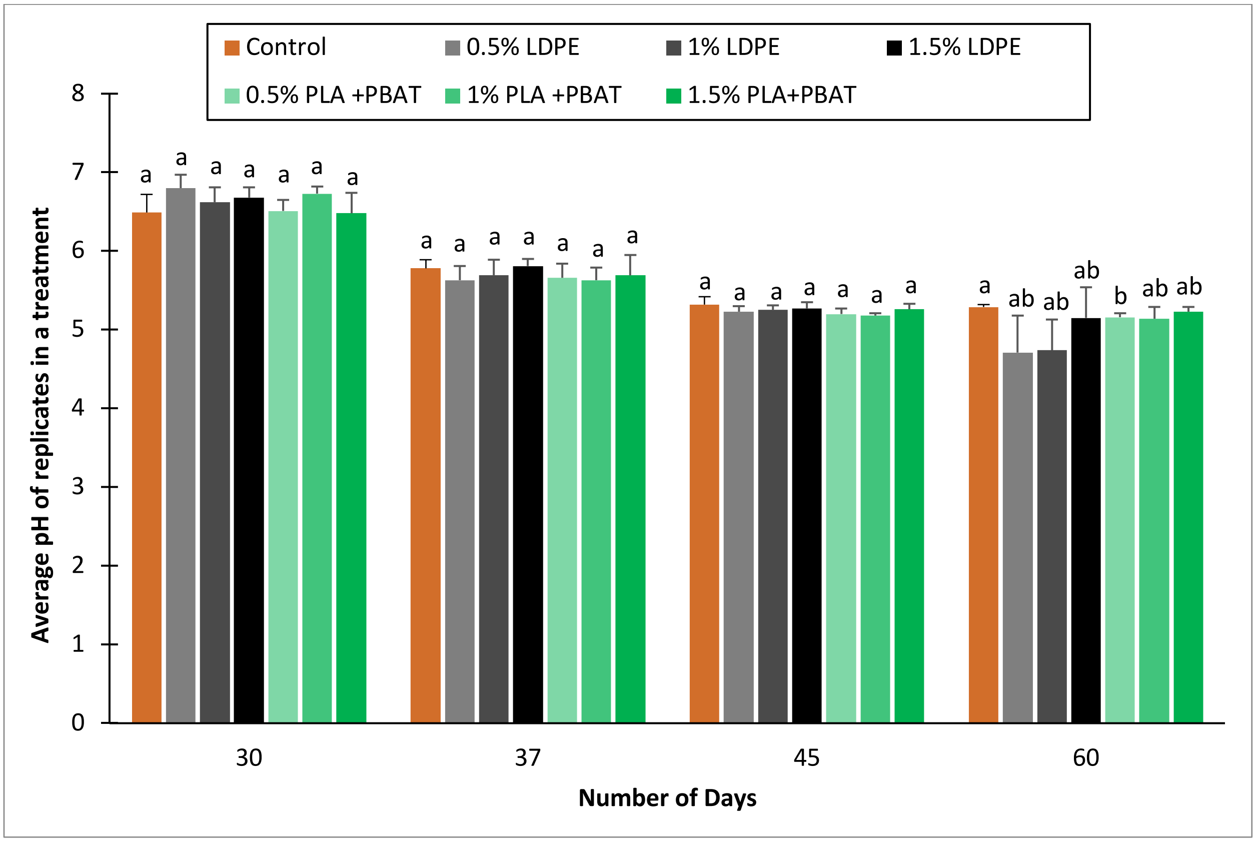

Figure 9: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the pH of the soil in time. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

The pH in the experiment significantly decreased over time. The microplastic treatments were not statistically significant compared to the control on all measurement days. At the conclusion of the trial, the 0.5% PLA+PBAT treatment's pH (4.71 ± 0.47) was significantly different from that of the control group (5.29 ± 0.03) and was slightly lower ($P < 0.05$).

4.2.2 The Effect of Microplastics on the EC of the Soil

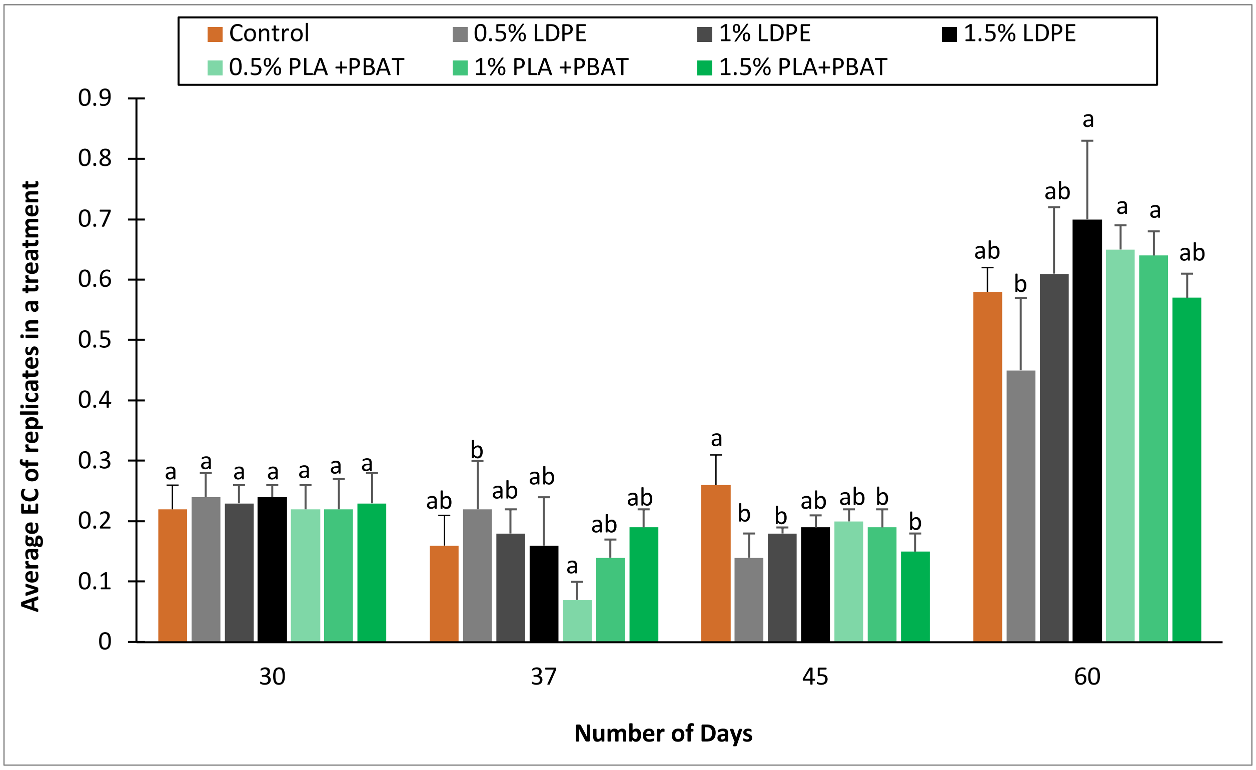

Figure 10: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the EC of the soil in time. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

In most of the treatments, the presence of microplastics did not have a significant impact on the electrical conductivity (EC) of the soil on all days of the measurement. However, on day 60, the treatment with 0.5% concentration of PLA+PBAT (0.65 ± 0.04) had a significantly higher EC than the treatment with 0.5% concentration of LDPE (0.45 ± 0.12) ($P < 0.05$). Furthermore, an increasing trend towards EC was observed in the LDPE treatments as the microplastic concentrations increased. Specifically, the 1.5% treatments exhibited a higher EC compared to the 0.5% and 1% LDPE treatments. On the other hand, an inverse correlation was observed between the EC levels and the concentration of microplastics in the PLA+PBAT treatments. Specifically, the PLA+PBAT treatment with higher microplastic concentration exhibited lower EC levels compared to the PLA+PBAT treatments with a concentration of 0.5% and 1%.

4.2.3 The Effect of Microplastics on the Emergence of Tomato Plants

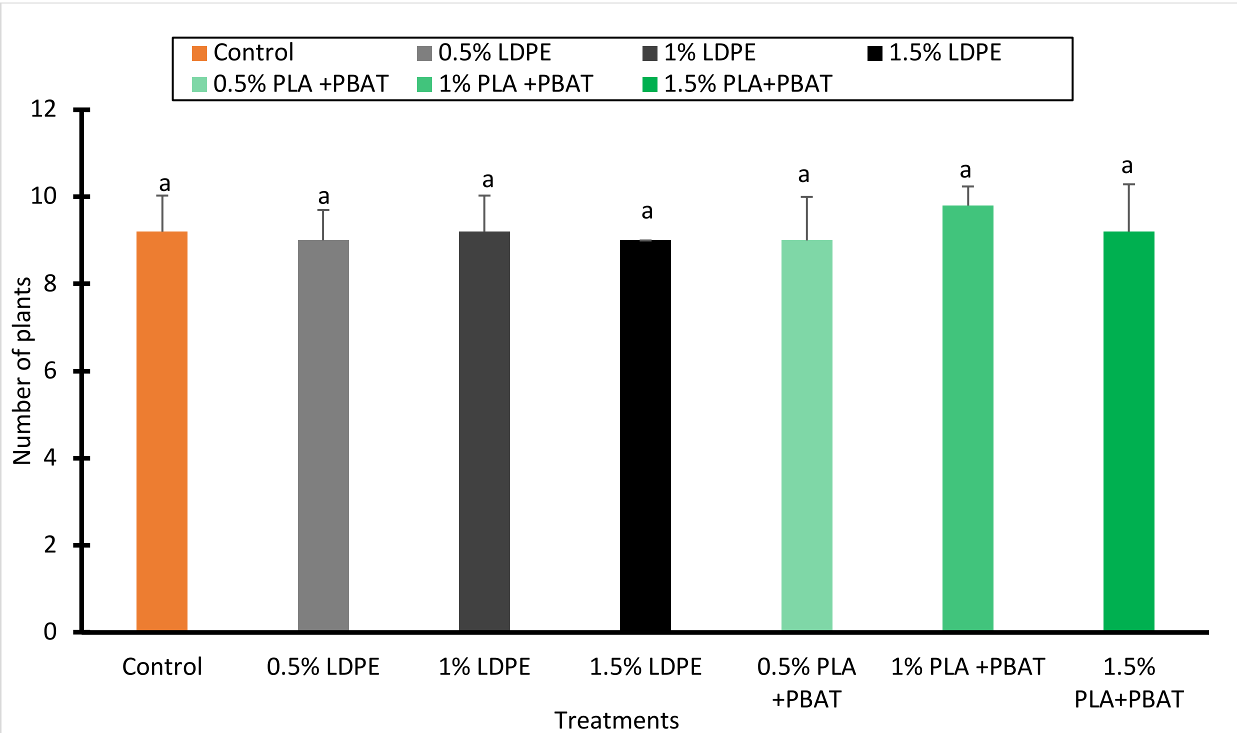

Figure 11: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the emergence of plants. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

The rate of emergence of tomato plants was not significantly impacted by microplastics in comparison to the corresponding control ($P > 0.05$).

4.2.4 The Effect of Microplastics on the Number of Leaves of Tomato Plants

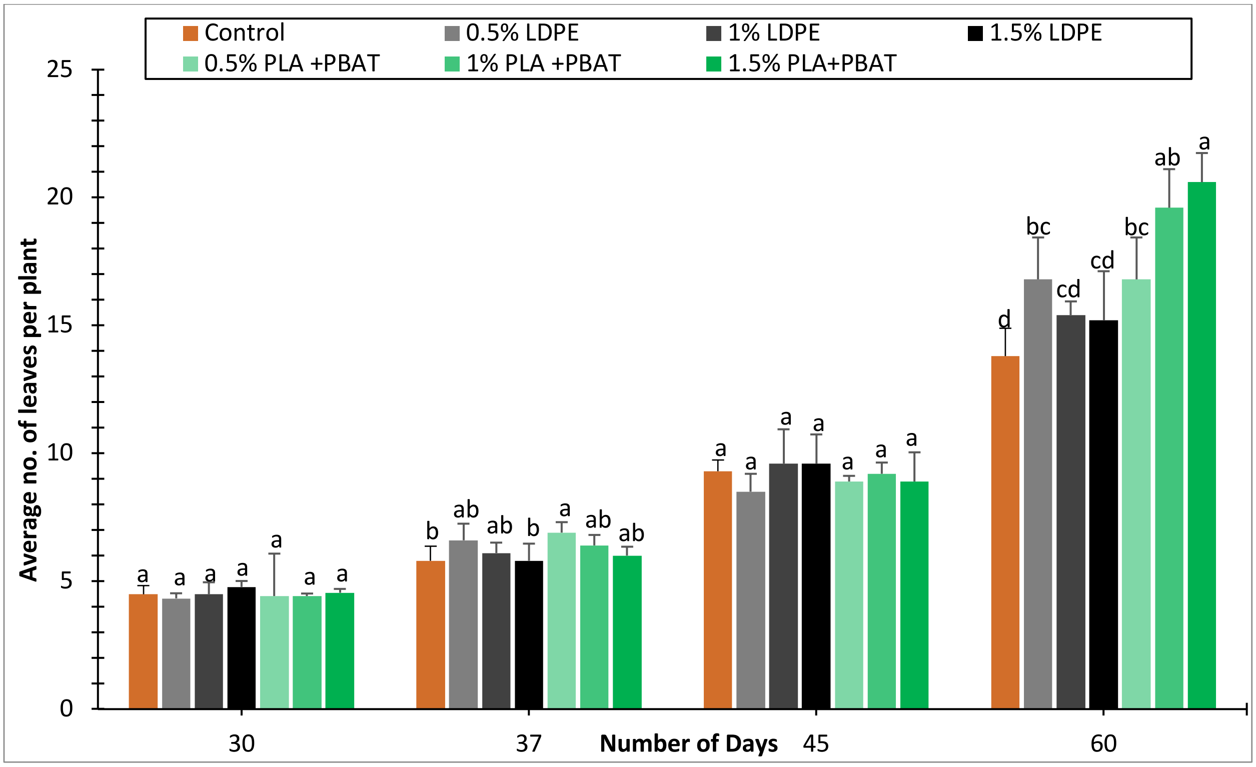

Figure 12: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the average number of leaves per plant per replicate in time. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

The effects of LDPE and PLA+PBAT microplastics of different concentrations compared to control at different intervals of time are shown in Figure 13. There was no effect of concentration on LDPE microplastic treatments. The PLA+PBAT treatments (20.60 ± 1.14 to 16.8 ± 1.64) had a significantly more average number of leaves than the control (13.80 ± 1.09) at the end of the experiment.

4.2.5 The Effect of Microplastics on the Height of Tomato Plants

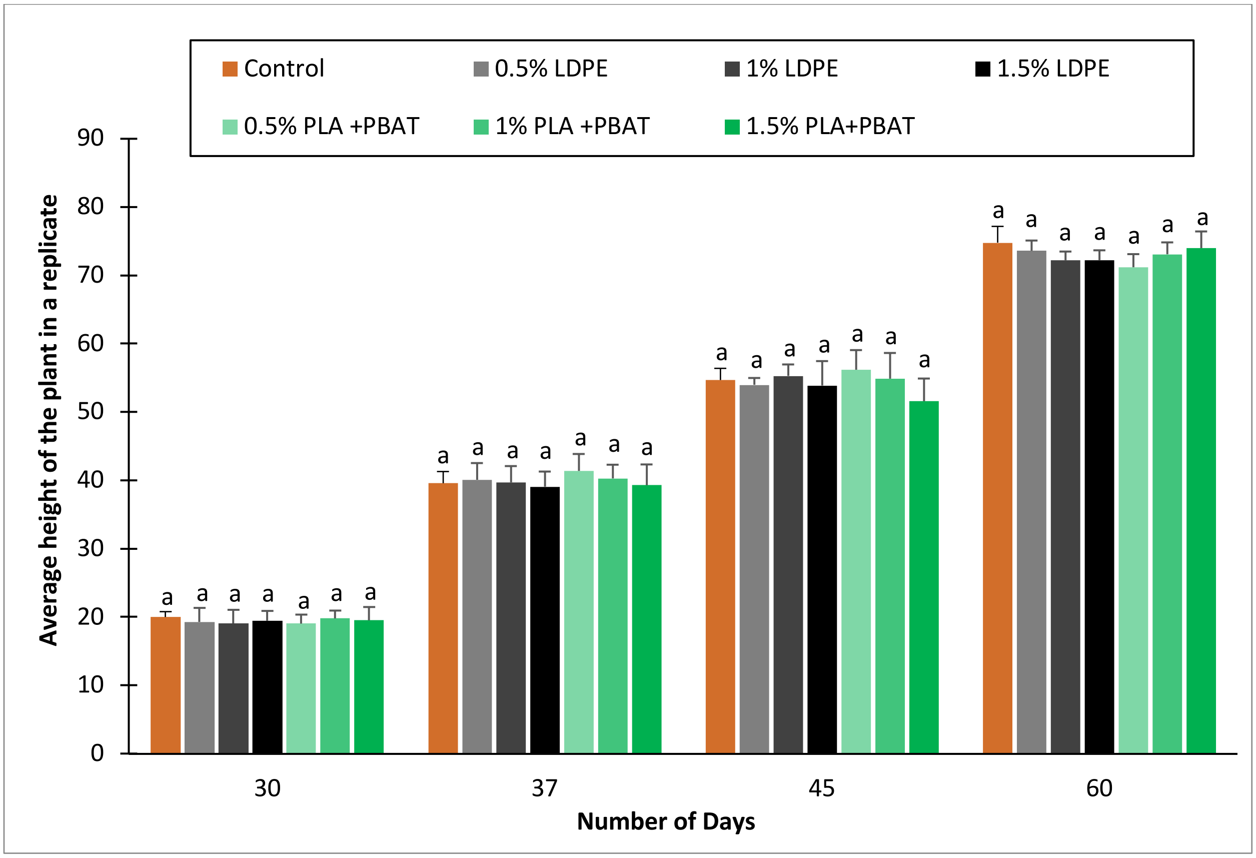

Figure 13: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the average height per plant per replicate in time. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

The study of the plant height over the growing season showed that the control treatments had the highest values compared to the microplastic treatments. The plant height (cm) varied between 74.80 ± 2.38 cm and 71.20 ± 1.92 cm. However, the results indicate that the presence of 0.5%, 1%, and 1.5% concentrations of PLA+PBAT and LDPE microplastics in the soil did not affect the plant's height compared to the control on all days of the measurements.

4.2.6 The Effect of Microplastics on the Chlorophyll Content of Tomato Plants

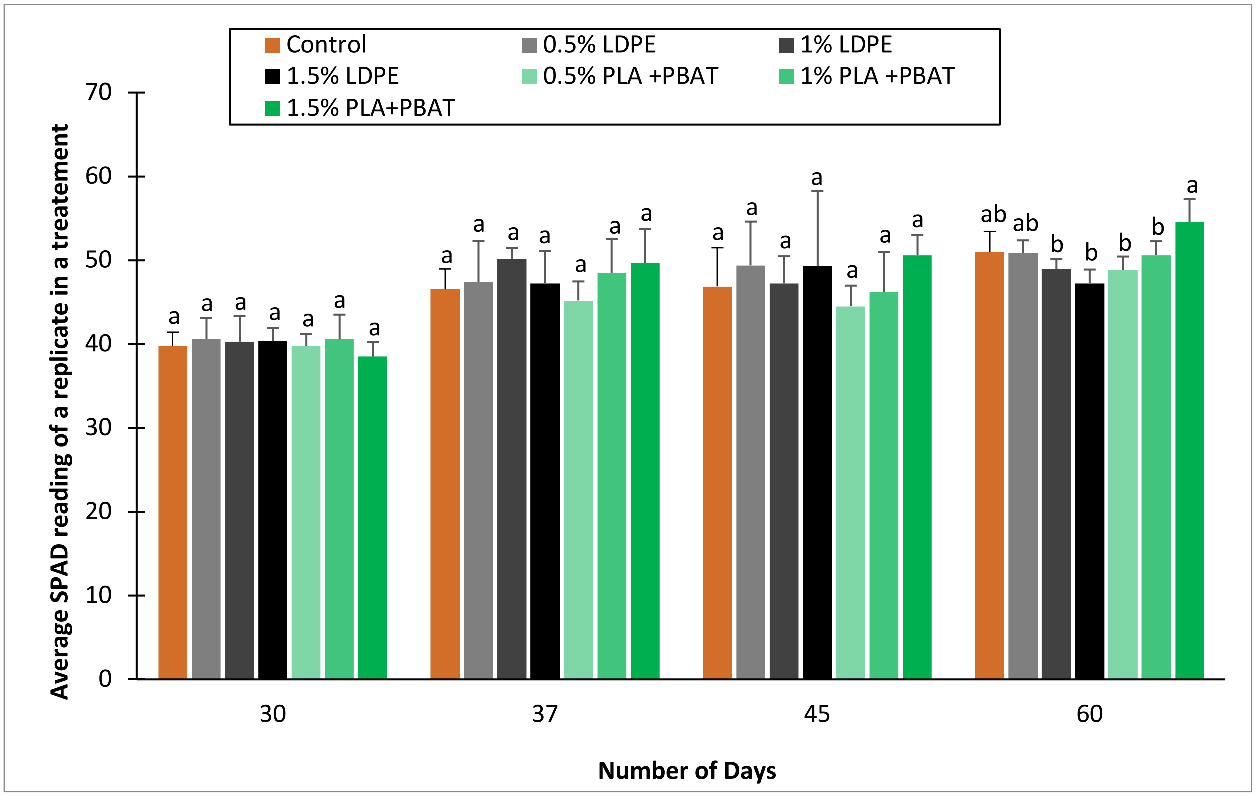

Figure 14: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the average SPAD reading per plant per replicate in time. Means with the same letter are not statistically different from one another ($P \leq 0.05$).

The presence of microplastics did not have a significant impact on chlorophyll content in most of the treatments on days 30, 37, and 45 of the measurement in comparison to the control. On day 60, the highest concentration of PLA+PBAT treatment had a significant increase in chlorophyll content compared to the lowest two concentrations.

4.2.7 The Effect of Microplastics on the Shoot Biomass of the Tomato Plants

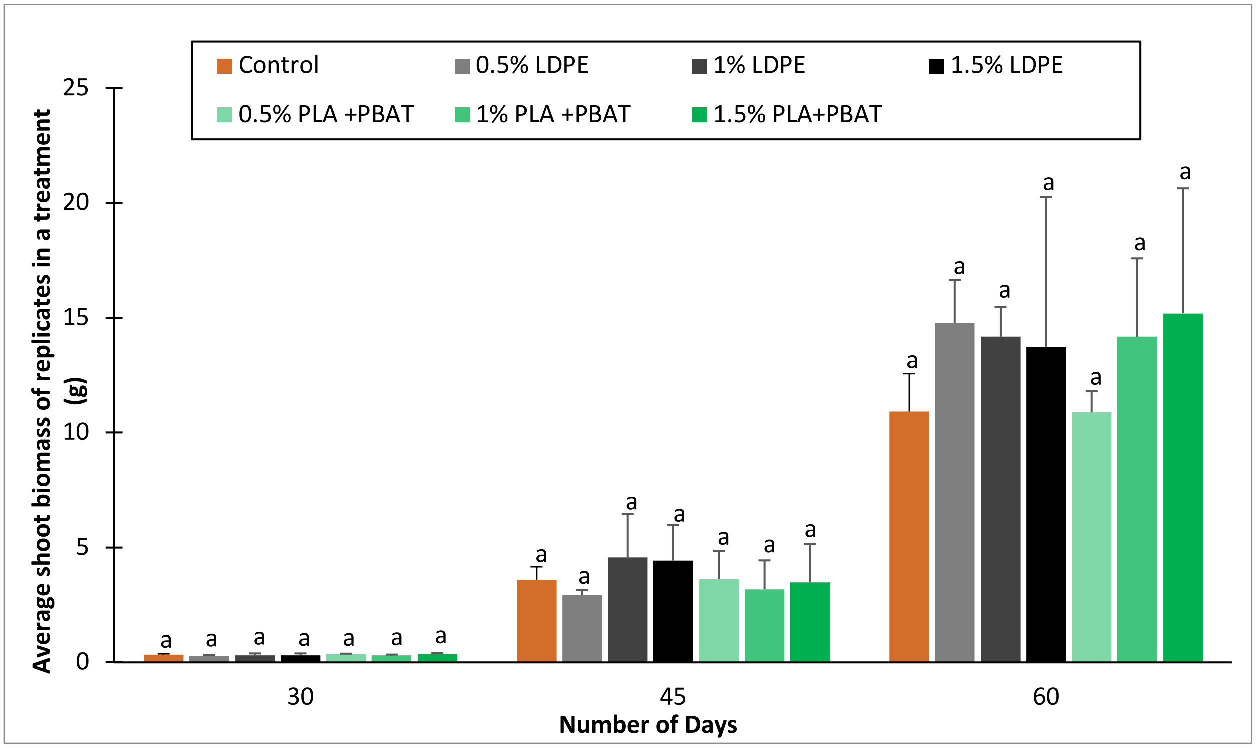

Figure 15: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the average shoot biomass per plant per replicate in time. Means followed by the same letter are not significantly different ($P \leq 0.05$).

The results suggest that the presence of 0.5%, 1%, and 1.5% concentrations of PLA+PBAT and LDPE microplastics in the soil did not result in a statistically significant difference in average shoot biomass compared to the control group on days 30, 37, 45 and 60 of the measurement in comparison to the control.

4.2.8 The Effect of Microplastics on the Root Biomass of the Tomato Plants

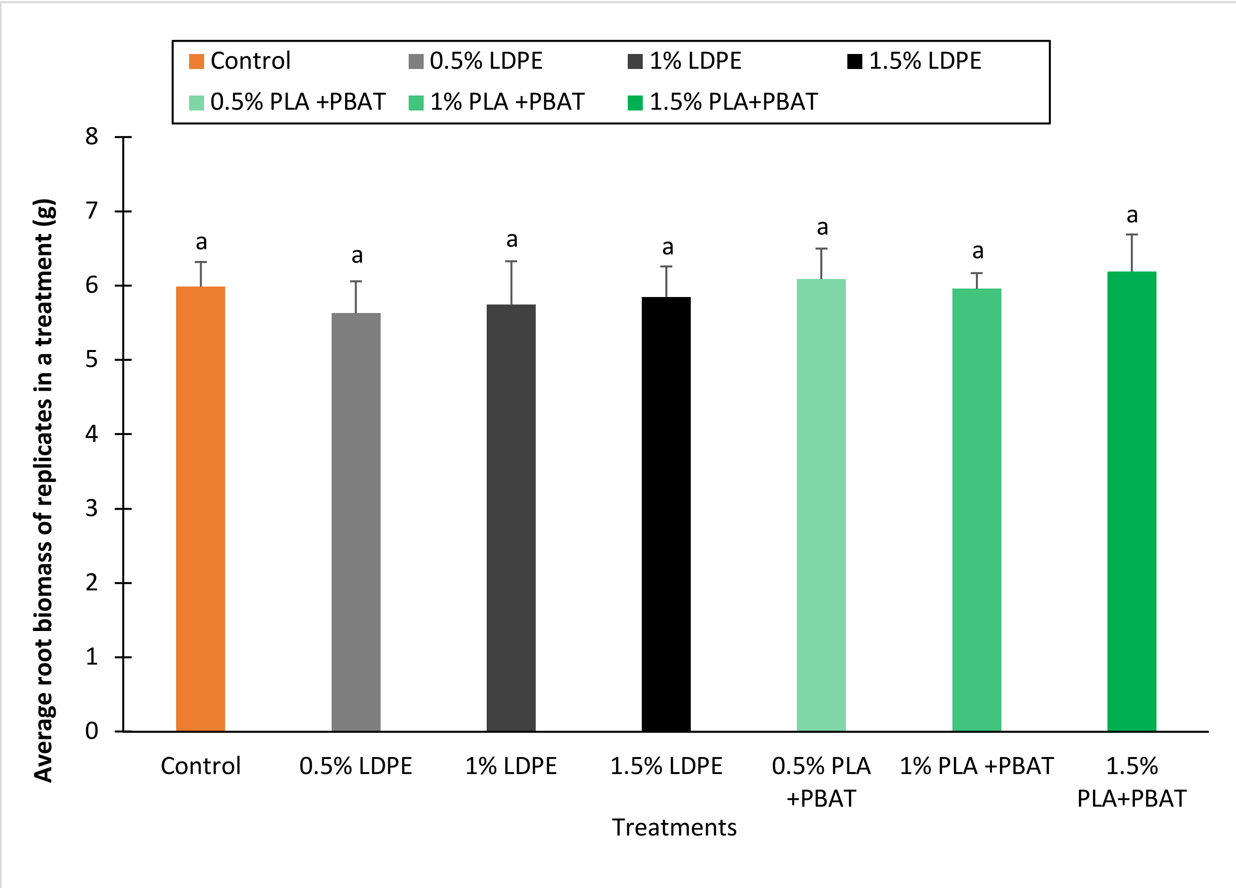

Figure 16: The impact of different concentrations of LDPE and PLA+PBAT microplastics on the average root biomass per plant per replicate in time. Means with the same letter are not statistically different from one another (P ≤ 0.05).

The results suggest that the presence of 0.5%, 1%, and 1.5% concentrations of PLA+PBAT and LDPE microplastics in the soil did not result in a statistically significant difference in average root biomass compared to the control group on days 60 of the measurement in comparison to the control.

4.3 Discussion of Results

The aim of this study was to examine the impact of PLA+PBAT and LDPE microplastics on some chemical properties of soil and the growth of plants.

The results of the experiments suggest that the presence of microplastics has an impact on soil pH. In the tomato experiment, the pH of the soil decreased over time, and the 0.5% PLA +PBAT treatment had a significantly lower pH compared to the control group ($P \leq 0.05$). This indicates that the presence of PLA+PBAT microplastics in the soil can contribute to a decrease in soil pH. Similarly, in the strawberry experiment, treatment groups saw significance between the interaction of the type and concentration ($P \leq 0.05$). The 1.5% PLA+PBAT treatment has more soil pH than the other treatments. The LDPE treatments with 1% and 1.5% microplastic concentrations has lower pH levels at the end of the experiment. The study suggests that the presence of microplastics can affect soil pH, and this effect may vary depending on the type of growth media used. The effects of this can extend to soil health and plant growth, given that soil pH plays a significant role in determining the accessibility of vital nutrients, the absorption of fertilizers, and the balance of ions within plants. As pH rises, the solubility of some fertilizers decreases, making it more difficult for plants to take up certain nutrients. Phosphorus, for example, becomes less available in alkaline soils. This can lead to reduced fertilizer efficiency and the need for higher fertilizer application rates to achieve the same nutrient uptake by plants (Mylavarapu et al., 2020). Similar findings were reported in earlier studies by Boots et al. (2019) and Qi et al. (2020). Boots et al. (2019) found that exposure to PE microplastics led to a significant decrease in soil pH when growing *Lolium perenne*, compared to control and PLA microplastics. Qi et al. (2020) on the other hand, reported an increase in soil pH for wheat plants treated with LDPE microplastics.

The results of the strawberry experiment showed that higher concentrations of both types of microplastics led to a decrease in the soil's electrical conductivity (EC) at the end of the experiment. These findings are consistent with the results reported by Qi et al., 2020, who also observed a decrease in EC after treatment with LDPE microplastics.

During the tomato experiment, it was observed that the 0.5% PLA+PBAT treatment concentration resulted in a significantly higher EC compared to the 0.5% LDPE treatment concentration. This finding indicates that the type of microplastics used has an impact on the soil's electrical conductivity. High soil EC can reduce water uptake by plants, as the presence of excess salts in the soil solution creates an osmotic potential that restricts the movement of water into plant roots. This can lead to water stress, causing stunted growth and reduced yields (Mylavarapu et al., 2020).

The study shows that microplastics did not impact the emergence rate, height, shoot biomass, or root biomass of tomato plants. This lends credence to the hypothesis that the presence of microplastics did not interfere with the germination, plant height, and root and shoot biomass of tomato seedlings. The results of our study align with previous research conducted by Sahasa et al., (2023), who found that exposing tomato seedlings to various concentrations of LDPE microplastics did not affect germination rates over time when compared to a control group. Similarly, Serrano-Ruiz et al., (2023) reported that LDPE fragments did not affect plant growth, which is consistent with our findings. Another study by Wang et al., (2020) found that the addition of 1% w/w HDPE did not affect maize growth. de Souza Machado et al., (2019) also observed that the presence of up to 2% w/w HDPE in soil did not significantly impact the structure of the soil or the development of onions.

The authors suggested that this limited effect could be attributed to the stable and non-nutritive chemical composition of $(C_2H_4)_n$ in HDPE. Our study specifically focused on LDPE, which shares a similar $(C_2H_4)_n$ structure but has a lower molecular weight. However, it was found that the presence of PLA+PBAT microplastics had a positive effect on plant growth, as evidenced by a higher number of leaves and greater chlorophyll concentrations. In particular, at a concentration of 1.5%, there was a significant increase in chlorophyll content compared to lower concentrations. This could be due to the stimulation of growth caused by the breakdown of PLA by-products into metabolites. PLA can be degraded into lactic acid oligomers by soil microbes (Torres et al., 1996). The exact mechanism by which microplastics in soil affect chlorophyll content remains unclear, but one of the possible explanations is that organic compounds produced during degradation mobilize nutrients, resulting in an impact on plant chlorophyll content.

5 Conclusions and Recommendations

5.1 Conclusions

The research revealed that the growth and development of tomato plants are not affected by the presence of LDPE microplastics up to a concentration of 1.5% in Agromix G6 media, as seen in the unchanged emergence rate, plant height, shoot biomass, and root biomass. However, the greater number of leaves and concentration of chlorophyll in tomatoes produced in soil with PLA+PBAT microplastics invite further investigation into the causal mechanisms. The potential effects of PLA+PBAT or similar polymers in the soil are interesting to growers, policymakers, and manufacturers of horticultural mulch films.

5.2 Recommendations

The study's results suggest that there exist multiple prospective domains for additional research:

- Research on the long-term effects of microplastics on plant growth and development: The current study concentrated on a brief period of time. Future research could investigate the impacts of microplastic exposure on plant growth, reproduction, and overall health.
- Comparison of different kinds of microplastics: This study compared the effects of two microplastic varieties, LDPE, and PLA+PBAT. Future research could examine the effects of additional types of microplastics, such as those used more frequently in horticulture.
- Analysis of microplastic degradation: Future studies could investigate the rate at which microplastics degrade in different soil types and conditions and the impact of microplastic degradation products on plant growth and development.
- Simulating the experiment in field conditions provide an opportunity to test plants or crops under natural, real-world conditions, including exposure to weather, pests, and diseases.

Field trials can often involve larger sample sizes than greenhouse experiments, increasing the statistical power and precision of the results.

In summary, the realm of microplastics in agriculture is a dynamic and evolving field, where research of the breakdown of microplastics into nanoplastics and the repercussions of nanoplastic exposure on plant growth are at the forefront. Simultaneously, investigations to understand how pesticides adsorb to plastic surfaces and how this interaction affects soil quality and the environment continue to uncover valuable insights for sustainable agricultural practices.

6 References

Agriculture & Agri-Food Canada (AAFC) (2010), Ottawa, Ontario. Plant Hardiness Zones. (Accessed 19 March 2023); Available from: https://www.arcgis.com/apps/mapviewer/index.html?webmap=717d1f52d75c4476a3f178636666932d.

Álvarez-Lopeztello, J., Robles, C., & del Castillo, R. F. (2021). Microplastic pollution in neotropical rainforest, savanna, pine plantations, and pasture soils in lowland areas of Oaxaca, Mexico: Preliminary results. *Ecological Indicators*, *121*, 107084. https://doi.org/10.1016/j.ecolind.2020.107084

Bakker, J. C. (1991). Leaf conductance of four glasshouse vegetable crops as affected by air humidity. *Agricultural and Forest Meteorology*, *55*(1), 23–36. https://doi.org/10.1016/0168-1923(91)90020-Q

Bandopadhyay, S., Martin-Closas, L., Pelacho, A. M., & DeBruyn, J. M. (2018). Biodegradable plastic mulch films: Impacts on soil microbial communities and ecosystem functions. *Frontiers in Microbiology*, *9*. https://www.frontiersin.org/articles/10.3389/fmicb.2018.00819

Blancard, D. (2012). 1—The tomato plant and its culture. In D. Blancard (Ed.), *Tomato Diseases (Second Edition)* (pp. 17–34). Academic Press, Cambridge, London. https://doi.org/10.1016/B978-0-12-387737-6.50001-7

Blanco, I., Loisi, R. V., Sica, C., Schettini, E., & Vox, G. (2018). Agricultural plastic waste mapping using GIS. A case study in Italy. *Resources, Conservation and Recycling*, *137*, 229–242. https://doi.org/10.1016/j.resconrec.2018.06.008

Bläsing, M., & Amelung, W. (2018). Plastics in soil: Analytical methods and possible sources. *The Science of the Total Environment*, *612*, 422–435. https://doi.org/10.1016/j.scitotenv.2017.08.086

Boots, B., Russell, C. W., & Green, D. S. (2019). Effects of microplastics in soil ecosystems: Above and Below Ground. *Environmental Science & Technology*, *53*(19), 11496–11506. https://doi.org/10.1021/acs.est.9b03304

Brady, N. C., & Weil, R. R. (2008). *The nature and properties of soils* (14th ed). Pearson Prentice Hall, Hoboken, New Jersey. http://catdir.loc.gov/catdir/toc/ecip0719/2007022182.html

Brodhagen, M., Goldberger, J. R., Hayes, D. G., Inglis, D. A., Marsh, T. L., & Miles, C. (2017). Policy considerations for limiting unintended residual plastic in agricultural soils. *Environmental Science & Policy*, *69*, 81–84. https://doi.org/10.1016/j.envsci.2016.12.014

Bunt, A. C. (1988). Media and mixes for container-grown plants: A manual on the preparation and use of growing media for pot plants, A.C. Bunt (2nd ed.). Unwin Hyman.

Cammarano, D., Ronga, D., Di Mola, I., Mori, M., & Parisi, M. (2020). Impact of climate change on water and nitrogen use efficiencies of processing tomato cultivated in Italy. *Agricultural Water Management*, *241*, 106336. https://doi.org/10.1016/j.agwat.2020.106336

Cantaliffe, D., Castellanos, J. Z., & Paranjpe, A. (2007). Yield and quality of greenhouse-grown strawberries as affected by nitrogen level in coco coir and pine bark media. *Proceedings of the Florida State Horticultural Society*, *120,1047*.

Capanoglu, E., Beekwilder, J., Boyacioglu, D., De Vos, R. C. H., & Hall, R. D. (2010). The effect of industrial food processing on potentially health-beneficial tomato antioxidants. *Critical Reviews in Food Science and Nutrition*, *50*(10), 919–930. https://doi.org/10.1080/10408390903001503

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation rates of plastics in the environment. *ACS Sustainable Chemistry & Engineering*, *8*(9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

Cleanfarms, (2021) Etobicoke, Ontario. Agricultural plastic characterization and management on Canadian farms. https://cleanfarms.ca/agricultural-plastic-characterization-and-management-on-canadian-farms/

Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin*, *62*(12), 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025

Cook, R., & Calvin, L. (n.d.). Greenhouse Tomatoes Change the Dynamics of the North American Fresh Tomato Industry , USDA, Washington, D.C. Retrieved June 28, 2023, from http://www.ers.usda.gov/publications/pub-details/?pubid=45477

Corradini, F., Casado, F., Leiva, V., Huerta-Lwanga, E., & Geissen, V. (2021). Microplastics occurrence and frequency in soils under different land uses on a regional scale. *Science of The Total Environment*, *752*, 141917. https://doi.org/10.1016/j.scitotenv.2020.141917

Courter, J. W. (1965). Plastic Greenhouses (1st Edition). University Of Illinois. https://www.biblio.com/book/plastic-greenhouses-courter-j-w/d/1512115178

Datta, S., Taghvaeian, S., & Stivers, J. (2017). Understanding soil water content and thresholds for irrigation management. https://doi.org/10.13140/RG.2.2.35535.89765

Davidson, H., Mecklenburg, R., & Peterson, C. (2000). Nursery management: Administration and culture (4th ed, Vol. 1–1 online resource (xii, 530 pages)). Prentice Hall, Hoboken, New Jersey. http://books.google.com/books?id=aAghAQAAMAAJ

de Souza Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., Becker, R., Görlich, A. S., & Rillig, M. C. (2019). Microplastics can change soil properties and affect plant performance. *Environmental Science & Technology*, *53*(10), 6044–6052. https://doi.org/10.1021/acs.est.9b01339

de Souza Machado, A. A., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., & Rillig, M. C. (2018). Impacts of microplastics on the soil biophysical environment. *Environmental Science & Technology*, *52*(17), 9656–9665. https://doi.org/10.1021/acs.est.8b02212

Dris, R., Gasperi, J., Saad, M., Mirande, C., & Tassin, B. (2016). Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin*, *104*(1–2), 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006

Durner, E. F., & Durner, E. F. (2018). Plant architecture of Albion strawberry (*Fragaria* × *ananassa*) is not influenced by light source during conditioning. *AIMS Agriculture and Food*, *3*(3), 246–265. https://doi.org/10.3934/agrfood.2018.3.246

European Bioplastics, 2016. An analysis of European plastics production, demand and waste data. https://www.european-bioplastics.org/bioplastics/

Food and Agriculture Organization of the United Nations, 2021. *Assessment of agricultural plastics and their sustainability: A call for action |Policy Support and Governance|* https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1460015/

Fuller, S., & Gautam, A. (2016). A procedure for measuring microplastics using pressurized fluid extraction. *Environmental Science & Technology*, *50*(11), 5774–5780. https://doi.org/10.1021/acs.est.6b00816

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782

Gianquinto, G., Sambo, P., & Borsato, D. (2006). Determination of SPAD threshold values for the optimisation of nitrogen supply in processing tomato. *Acta Horticulturae*, *700*, 159–166. https://doi.org/10.17660/ActaHortic.2006.700.26

Government of Canada, S. C. (2022). Area, production and farm gate value of marketed fruits. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210036401

Guo, J.-J., Huang, X.-P., Xiang, L., Wang, Y.-Z., Li, Y.-W., Li, H., Cai, Q.-Y., Mo, C.-H., & Wong, M.-H. (2020). Source, migration and toxicology of microplastics in soil. *Environment International*, *137*, 105263. https://doi.org/10.1016/j.envint.2019.105263

Guo, L., Bornø, M. L., Niu, W., & Liu, F. (2021). Biochar amendment improves shoot biomass of tomato seedlings and sustains water relations and leaf gas exchange rates under different irrigation and nitrogen regimes. *Agricultural Water Management*, *245*, 106580. https://doi.org/10.1016/j.agwat.2020.106580

Hancock, J. F., Sjulin, T. M., & Lobos, G. A. (2008). Strawberries. In J. F. Hancock (Ed.), Temperate Fruit Crop Breeding: Germplasm to Genomics (pp. 393–437). Springer Netherlands. https://doi.org/10.1007/978-1-4020-6907-9_13

Hellman, E. W., & Travis, J. D. (1988). Growth inhibition of strawberry at high temperatures. *Advances in Strawberry Production (USA)*. https://scholar.google.com/scholar_lookup?title=Growth+inhibition+of+strawberry+at+high+temperatures&author=Hellman%2C+E.W.&publication_year=1988

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. *Environmental Science & Technology*, *46*(6), 3060–3075. https://doi.org/10.1021/es2031505

Huang, Y., Liu, Q., Jia, W., Yan, C., & Wang, J. (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environmental Pollution*, *260*, 114096. https://doi.org/10.1016/j.envpol.2020.114096

Issac, M. N., & Kandasubramanian, B. (2021). Effect of microplastics in water and aquatic systems. *Environmental Science and Pollution Research*, *28*(16), 19544–19562. https://doi.org/10.1007/s11356-021-13184-2

Johnston, A. M., & Bruulsema, T. W. (2014). 4R nutrient stewardship for improved nutrient use efficiency. *Procedia Engineering*, *83*, 365–370. https://doi.org/10.1016/j.proeng.2014.09.029

Kasirajan, S., & Ngouajio, M. (2012). Polyethylene and biodegradable mulches for agricultural applications: A review. *Agronomy for Sustainable Development*, *32*(2), 501–529. https://doi.org/10.1007/s13593-011-0068-3

Kim, H.-Y. (2015). Statistical notes for clinical researchers: Post-hoc multiple comparisons. *Restorative Dentistry & Endodontics*, *40*(2), 172–176. https://doi.org/10.5395/rde.2015.40.2.172

Krucker, M., Hummel, R. L., & Cogger, C. (2010). Chrysanthemum production in composted and noncomposted organic waste substrates fertilized with nitrogen at two rates using surface and subirrigation. *HortScience*, *45*(11), 1695–1701. https://doi.org/10.21273/HORTSCI.45.11.1695

Kyrikou, I., & Briassoulis, D. (2007). Biodegradation of agricultural plastic films: A Critical Review. *Journal of Polymers and the Environment*, *15*(2), 125–150. https://doi.org/10.1007/s10924-007-0053-8

Lamarre, M., & Lareau, M. J. (1997). Influence of nitrogen, potassium and magnesium fertilization on day-neutral strawberries in Quebec. *Acta Horticulturae*, *439*, 701–704. https://doi.org/10.17660/ActaHortic.1997.439.117

Li, B., Huang, S., Wang, H., Liu, M., Xue, S., Tang, D., Cheng, W., Fan, T., & Yang, X. (2021). Effects of plastic particles on germination and growth of soybean (*Glycine max*): A pot experiment under field condition. *Environmental Pollution*, *272*, 116418. https://doi.org/10.1016/j.envpol.2020.116418

Li, C., Moore-Kucera, J., Miles, C., Leonas, K., Lee, J., Corbin, A., & Inglis, D. (2014). Degradation of potentially biodegradable plastic mulch films at three diverse U.S. locations. *Agroecology and Sustainable Food Systems*, *38*(8), 861–889. https://doi.org/10.1080/21683565.2014.884515

Li, H., Song, F., Song, X., Zhu, K., Lin, Q., Zhang, J., & Ning, G. (2023). Single and composite damage mechanisms of soil polyethylene/polyvinyl chloride microplastics to the photosynthetic performance of soybean (*Glycine max* [L.] merr.). *Frontiers in Plant Science*, *13*. https://www.frontiersin.org/articles/10.3389/fpls.2022.1100291

Lieten, P., Evenhuis, B., & Baruzzi, G. (2005). Cold storage of strawberry plants. *International Journal of Fruit Science*, *5*(1), 75–82. https://doi.org/10.1300/J492v05n01_07

Liu, H., Yang, X., Liu, G., Liang, C., Xue, S., Chen, H., Ritsema, C. J., & Geissen, V. (2017). Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. *Chemosphere*, *185*, 907–917. https://doi.org/10.1016/j.chemosphere.2017.07.064

Liu, W., Liu, K., Chen, D., Zhang, Z., Li, B., El-Mogy, M. M., Tian, S., & Chen, T. (2022). *Solanum lycopersicum*, a model plant for the studies in developmental biology, stress biology and food science. Foods, 11(16), 2402. https://doi.org/10.3390/foods11162402

McKean, T., Kroggel, M., Kubota, C., & Naasz, R. (2020). Evaluation of four soilless substrate systems for greenhouse strawberry production. Acta Horticulturae, 1296, 823–830. https://doi.org/10.17660/ActaHortic.2020.1296.104

Mylavarapu, R., Bergeron, J., Wilkinson, N., & Hanlon, E. A. (2020). Soil pH and Electrical Conductivity: A County Extension Soil Laboratory Manual: CIR1081/SS118, rev. 1/2020. EDIS, 2020(1), Article 1. https://doi.org/10.32473/edis-ss118-2020

Nelson, P. V. (2003). Greenhouse operation and management (6th ed). Prentice Hall, Hoboken, NewJersey.

Niaounakis, M. (2013). 2—Definitions and assessment of (Bio)degradation. In M. Niaounakis (Ed.), *Biopolymers Reuse, Recycling, and Disposal* (pp. 77–94). William Andrew Publishing. https://doi.org/10.1016/B978-1-4557-3145-9.00002-6

Novák, V., & Hlaváčiková, H. (2019). Soil-water content and its measurement. In V. Novák & H. Hlaváčiková (Eds.), *Applied Soil Hydrology* (pp. 49–61). Springer International Publishing, Berlin, Germany. https://doi.org/10.1007/978-3-030-01806-1_5

Orde, K. M., Marini, R., Demchak, K., & Sideman, R. (2021). Albion strawberry responds to mulch treatments and low tunnels covered with photoselective films. *HortScience*, *56*(9), 1005–1014. https://doi.org/10.21273/HORTSCI15886-21

Özer, H., & Dede, Ö. H. (2018). Improving physical properties of plant growing medias using perlite. *Sakarya University Journal of Science*, *22*(5), Article 5. https://doi.org/10.16984/saufenbilder.382895

Palansooriya, K. N., Shi, L., Sarkar, B., Parikh, S. J., Sang, M. K., Lee, S.-R., & Ok, Y. S. (2022). Effect of LDPE microplastics on chemical properties and microbial communities in soil. *Soil Use and Management*, *38*(3), 1481–1492. https://doi.org/10.1111/sum.12808

Papadopoulos, A. P., & Tan, C. S. (1991). Irrigation of greenhouse tomatoes grown in “Harrow” peat-bags. *Canadian Journal of Plant Science*, *71*(3), 947–949. https://doi.org/10.4141/cjps91-136

PlasticsEurope (2021), Brussels, Belgium. Plastics - the Facts: An analysis of European plastics production, demand, and waste data. (Accessed 12 January 2023); Available from: https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/

Qi, Y., Ossowicki, A., Yang, X., Huerta Lwanga, E., Dini-Andreote, F., Geissen, V., & Garbeva, P. (2020). Effects of plastic mulch film residues on wheat rhizosphere and soil properties. *Journal of Hazardous Materials*, *387*, 121711. https://doi.org/10.1016/j.jhazmat.2019.121711

Rai, R. K., Singh, V. P., & Upadhyay, A. (2017). Chapter 17—Soil Analysis. In R. K. Rai, V. P. Singh, & A. Upadhyay (Eds.), *Planning and Evaluation of Irrigation Projects* (pp. 505–523). Academic Press, Cambridge, London. https://doi.org/10.1016/B978-0-12-811748-4.00017-0

Ramos, L., Berenstein, G., Hughes, E. A., Zalts, A., & Montserrat, J. M. (2015). Polyethylene film incorporation into the horticultural soil of small periurban production units in Argentina. *Science of The Total Environment*, *523*, 74–81. https://doi.org/10.1016/j.scitotenv.2015.03.142

Rezende Fontes, P. C., & de Araujo, C. (2006). Use of a chlorophyll meter and plant visual aspects for nitrogen management in tomato fertigation. *Journal of Applied Horticulture, 8(1), 8-11.* https://doi.org/10.37855/jah.2006.v08i01.02

Rillig, M. C. (2012). Microplastic in terrestrial ecosystems and the soil? *Environmental Science & Technology*, *46*(12), 6453–6454. https://doi.org/10.1021/es302011r

Rillig, M. C., Leifheit, E., & Lehmann, J. (2021). Microplastic effects on carbon cycling processes in soils. *PLOS Biology*, *19*(3), e3001130. https://doi.org/10.1371/journal.pbio.3001130

Rochman, C. M. (2018). Microplastics research—From sink to source. *Science*, *360*(6384), 28–29. https://doi.org/10.1126/science.aar7734

Rochman, C. M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., Athey, S., Huntington, A., McIlwraith, H., Munno, K., De Frond, H., Kolomijeca, A., Erdle, L., Grbic, J., Bayoumi, M., Borrelle, S. B., Wu, T., Santoro, S., Werbowski, L. M., … Hung, C. (2019). Rethinking microplastics as a diverse contaminant suite. *Environmental Toxicology and Chemistry*, *38*(4), 703–711. https://doi.org/10.1002/etc.4371

Ronga, D., Parisi, M., Pentangelo, A., Mori, M., & Di Mola, I. (2019). Effects of nitrogen management on biomass production and dry matter distribution of processing tomato cropped in southern Italy. *Agronomy*, *9*(12), Article 12. https://doi.org/10.3390/agronomy9120855

Sahasa, R. G. K., Dhevagi, P., Poornima, R., Ramya, A., Moorthy, P. S., Alagirisamy, B., & Karthikeyan, S. (2023). Effect of polyethylene microplastics on seed germination of Blackgram (*Vigna mungo* L.) and Tomato (*Solanum lycopersicum* L.). *Environmental Advances*, *11*, 100349. https://doi.org/10.1016/j.envadv.2023.100349

Scheurer, M., & Bigalke, M. (2018). Microplastics in Swiss floodplain soils. *Environmental Science & Technology*, *52*(6), 3591–3598. https://doi.org/10.1021/acs.est.7b06003

Schmilewski, G. (2009). Growing medium constituents used in the EU. *Acta Horticulturae*, *819*, 33–46. https://doi.org/10.17660/ActaHortic.2009.819.3

Schumacher, B. A., Shines, K. C., Burton, J. V., & Papp, M. L. (1990). Comparison of Three Methods for Soil Homogenization. *Soil Science Society of America Journal*, *54*(4), 1187–1190. https://doi.org/10.2136/sssaj1990.03615995005400040046x

Scott, E. G., & Bearce, B. C. (1972). Hardwood-bark-sawdust compost for greenhouse pot flower production. *Forest Prod J*, 9, 22-36.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., & Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, *99*(3), 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

Serrano-Ruiz, H., Martin-Closas, L., & Pelacho, A. M. (2021). Biodegradable plastic mulches: Impact on the agricultural biotic environment. *Science of the Total Environment*, *750*, 141228. https://doi.org/10.1016/j.scitotenv.2020.141228

Serrano-Ruiz, H., Martin-Closas, L., & Pelacho, A. M. (2023). Impact of buried debris from agricultural biodegradable plastic mulches on two horticultural crop plants: Tomato and lettuce. *Science of The Total Environment*, *856*, 159167. https://doi.org/10.1016/j.scitotenv.2022.159167

Shamshiri, R. R., Jones, J. W., Thorp, K. R., Ahmad, D., Man, H. C., & Taheri, S. (2018). Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: A review. *International Agrophysics*, *32*, 287–302. https://doi.org/10.1515/intag-2017-0005

Shaw, D. V., & Larson, K. D. (2006). *Strawberry plant named 'Albion'* (United States Patent No. USPP16228P3). https://patents.google.com/patent/USPP16228P3/en

Sintim, H. Y., Bandopadhyay, S., English, M. E., Bary, A. I., DeBruyn, J. M., Schaeffer, S. M., Miles, C. A., Reganold, J. P., & Flury, M. (2019). Impacts of biodegradable plastic mulches on soil health. *Agriculture, Ecosystems & Environment*, *273*, 36–49. https://doi.org/10.1016/j.agee.2018.12.002

Soval-Villa, M., Wood, C. W., & Guertal, E. A. (2002). Tomato leaf chlorophyll meter readings as affected by variety, nitrogen form, and nighttime nutrient solution strength. *Journal of Plant Nutrition*, *25*(10), 2129–2142. https://doi.org/10.1081/PLN-120014065

Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., Muñoz, K., Frör, O., & Schaumann, G. E. (2016). Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? *Science of The Total Environment*, *550*, 690–705. https://doi.org/10.1016/j.scitotenv.2016.01.153

Sudan Acharya, M., Rauchecker, M., & Wu, W. (2014). Determination of water absorption and water holding capacities of different soil mixtures with MINIDRAIN system to enhance the plant growth. *EGU General Assembly Conference*, Vienna, Austria, (pp. 11571). https://ui.adsabs.harvard.edu/abs/2014EGUGA..1611571S/abstract

Torres, A., Li, S. M., Roussos, S., & Vert, M. (1996). Poly(lactic acid) degradation in soil or under controlled conditions. *Journal of Applied Polymer Science*, *62*(13), 2295–2302. https://doi.org/10.1002/(SICI)1097-4628(19961226)62:13<2295::AID-APP14>3.0.CO;2-2

U.S. Environmental Protection Agency, (2012). Ecological Effects Test Guidelines OCSPP 850.4100: Seedling Emergence and Seedling Growth. Office of Chemical Safety and Pollution Prevention, EPA 712-C-012, January 2013.

Wan, Y., Wu, C., Xue, Q., & Hui, X. (2019). Effects of plastic contamination on water evaporation and desiccation cracking in soil. *Science of The Total Environment*, *654*, 576–582. https://doi.org/10.1016/j.scitotenv.2018.11.123

Wang, F., Zhang, X., Zhang, S., Zhang, S., & Sun, Y. (2020). Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. *Chemosphere*, *254*, 126791. https://doi.org/10.1016/j.chemosphere.2020.126791

Wright, R. J., Erni-Cassola, G., Zadjelovic, V., Latva, M., & Christie-Oleza, J. A. (2020). Marine Plastic Debris: A New Surface for Microbial Colonization. *Environmental Science & Technology*, *54*(19), 11657–11672. https://doi.org/10.1021/acs.est.0c02305

Zhang, D., Liu, H., Hu, W., Qin, X., Ma, X., Yan, C., & Wang, H. (2016). The status and distribution characteristics of residual mulching film in Xinjiang, China. *Journal of Integrative Agriculture*, *15*(11), 2639–2646. https://doi.org/10.1016/S2095-3119(15)61240-0

Zhang, D., Ng, E. L., Hu, W., Wang, H., Galaviz, P., Yang, H., Sun, W., Li, C., Ma, X., Fu, B., Zhao, P., Zhang, F., Jin, S., Zhou, M., Du, L., Peng, C., Zhang, X., Xu, Z., Xi, B., … Liu, H. (2020). Plastic pollution in croplands threatens long-term food security. *Global Change Biology*, *26*(6), 3356–3367. https://doi.org/10.1111/gcb.15043

Zhang, G. S., & Liu, Y. F. (2018). The distribution of microplastics in soil aggregate fractions in southwestern China. *The Science of the Total Environment*, *642*, 12–20. https://doi.org/10.1016/j.scitotenv.2018.06.004