Bye-Bye Plastic Mulch: A Novel Mulch Film with Reduced Leachate Toxicity as an Alternative to Conventional Plastic and Biodegradable Mulch Films

Abstract

The introduction of novel entities has far passed the determined planetary boundary, a novel entity of focus has been micro(nano)plastics. One of the main sources of micro(nano) plastics in the body is from food. After entering the body, various complications can occur. For example, research has found that micro(nano)plastics have a tendency to accumulate in the brain. One of the main ways that microplastics are entering plant systems is from plastic mulching in soil. Though many biodegradable alternatives are emerging, recent studies have found them to leach harmful or underresearched substances that creates a risk of pollution swapping. The objective of this project is to develop a toxic-leachate free film by forming a nano-fibrous film using the biopolymers; pullulan, cellulose, and pectin.

Problem

Microplastics are widely defined as fragments of plastic between the sizes of 1 nanometer and 5 millimeters. Most microplastics arise from the slow disintegration of larger plastic products such as packaging, polyester clothing, and artificial turf. Due to their persistence and the widespread use of plastics, microplastics have become ubiquitous in nature. In 2020 alone, an estimated 2.7 million tons of microplastic entered the environment.

The problem arises as microplastics enter the human body through dermal contact, inhalation, and ingestion. A study conducted in 2019 estimated that an average human can consume up to 52 000 microplastic particles every year. Beyond direct human exposure, microplastics are still posing to be harmful. Micro(nano)plastics are increasingly being found in agricultural soils, posing additional concerns about the impact on human health, crop yield, and soil health.

Furthermore, Research indicates that the accumulation of microplastics in soil can negatively affect plant growth and reduce soil fertility, ultimately hindering agricultural yields. One of the primary contributors of microplastic pollution in agricultural soils is from plastic mulching. Though these films do have extensive benefits for the soil such as retaining moisture and preventing weed growth, they can break down to form tiny plastic particles.

Though biodegradable mulching has emerged, recent research has brought forward concerns of toxic leachates found in these films during their degradation. As a result, there are no conventionally available options of mulching that can be applied without producing microplastics or leaching harmful substances. This highlights a critical gap in sustainable agriculture practices, showcasing a need for a safer, non-toxic alternative.

Objective

The objective of this project is to develop and evaluate a biodegradable agricultural film that minimizes toxic leachates while maintaining performance comparable to commercially available biodegradable and conventional plastic mulching films.

Objective 1: Minimizing harmful leachates

The developed biodegradable film must produce safe, non-toxic leachates, minimizing harm to soil health, plant growth, surrounding ecosystems, and human health. This will be assessed through thorough leachate testing on seed germination.

Objective 2: Similar effectiveness to commercially available biodegradable films

The developed biodegradable film must demonstrate similar effectiveness to commercially available biodegradable and plastic mulch films. Performance will be assessed against commonly available films (polyethylene films) under controlled conditions. The developed biodegradable film will be considered successful if its measured “effectiveness” meet or exceed those of commercially available plastic and biodegradable mulch films, or fall within a maximum deviation of 10% where trade-offs are necessary.

As part of objective 2, the following attributes will be assessed:

- Physical properties
- Mechanical properties

Literature Review

The nine planetary boundary framework identifies 9 processes for the Earth system to stay stable. Novel entities have entered the high-risk zone. New chemicals are entering the Earth yearly and disrupting natural ecosystems. Novel entities are defined as truly novel anthropogenic introductions. These entities are introduced quickly without thoroughly considering all the consequences. However, they can have terrible impacts, as seen with DDT and chlorofluorocarbons (CFCs). This means the only way to implement a novel entity safely is by evaluating all aspects and potential harm. There are a variety of chemicals that are considered novel entities, but microplastics particularly stand out due to their rapidly increasing numbers.

Microplastics are plastics smaller than 5 millimetres. Current technology doesn't allow us to accurately quantify population-level microplastics or how much they accumulate in bodies or the impacts on health. However, human cell and animal testing is increasingly alarming many.

From trash, dust, cosmetics, cleaning products, to even human breast milk and meconium, an infant's first feces, microplastics are being encountered everywhere.

Though the impacts of microplastics are not fully understood, there is some known information:

- Nanoplastics, plastics smaller than 1 micrometer, pose even greater worries to scientists as they can infiltrate cells.
- In cell cultures, marine wildlife and animals show that microplastics can lead to cell damage, oxidative stress, and DNA damage.
- Studies in mice show the impacts of microplastics on reproductive health as well.

All this information is extremely alarming, showing risks for terrible impacts to human health.

micro(nano)plastics MNP are increasingly being found in agricultural soils, posing concerns about the impact on human health, crop yield, soil health, and more. Though research is still limited, the impacts of (MNPs) on plants are generally found to be negative. It is also very difficult to understand the effects of MNPs due to their extremely small size. In 2021, a study was done on polystyrene nanoplastics and their impact on the physiology and molecular metabolism of corn. It was found that after 15 days of exposure, the photosynthetic characteristics remained stable. The maximum photochemical quantum yield and non-photochemical quenching coefficient were stable. However, the root microstructure was damaged, and an antioxidant enzyme was activated. Additionally, malondialdehyde (MDA) increased by 2.25-4.50 fold. MDA is an enzyme that is formed after lipid peroxidation. This enzyme is a marker of oxidative stress. And the 100nm + 300 nm polystyrene nanoplastics caused an increase in activity of the root superoxide dismutase (SOD) by 1.28 and 1.53 fold, respectively. These statistics continue to demonstrate the harmful impacts of MNPs on plant health.

Another study in 2023 reviewed nanoplastic uptake, toxicity, and detoxification and made fascinating observations. Firstly, uptake was done through apoplastic and symplastic pathways through the process of transpiration. Responses include:

Physiological Responses	- Oxidative stress - Disturbed homeostasis
Morphological Responses	- Inhibited seedling growth - Reduced biomass accumulation - Modulated plant growth indices - Declined yield
Biochemical Responses	- Altered antioxidative enzymes - Interfered with photosynthesis

It is evident that microplastics not only pose threats to human health but also crop yield, having the potential to impact people on a global scale.

Most MNPs enter agricultural soil through irrigation or mulch filming. Mulch provides many benefits to the soil, such as water security, weed control, and temperature control. And more. Considerable field measurements show that plastic mulch raised crop water use efficiency by 40-85%. The application of plastic mulch also reduced the use of water by 30-45% while maintaining high soil moisture. This shows the application of mulching in water conservation in areas with scarce water. Plastic mulch suppresses soil evaporation by 42-47% in a maize field, which can also help prevent extreme precipitation from evapotranspiration, a form of precipitation accounting for 42% of extreme precipitation.

Furthermore, another study found that temperature was modulated by 4-5 degrees Celsius, with the colour of mulches impacting temperature. With different colours resulting in different temperature differences. White/reflective mulches kept the soil cool, black mulch raised the temperature, while clear mulch raised the temperature the most.

Not only can the colour of mulch films control temperature, but by using colours, yield can also be increased. Phytochrome is a protein in plants which is able to sense light. It exists in two forms: Pr (absorbing light) and Pfr (absorbing far-red light). When Pr is activated, the flower puts energy into creating the flower, while Pfr causes the plant to spend energy on leaning towards the light source. This concept can be used to increase yield. For example, red plastic mulch generated around 20% more tomatoes in certain trials. This proves how the plastic mulch film affects the microclimate of a plant.

Studies in China saw that there was roughly 15-50% more yield where cotton was mulched.

To address the microplastic problem, many biodegradable mulch films (BDMs) have arisen in the market. However, BDMs are being observed for having a higher leaching potential of inorganic and organic additives. These additives can easily leach into the environment as they are not chemically bound, and they either have negative impacts on crops or humans or are underresearched. This poses the risk of pollution swapping. An evaluation done on BDMs in 2025 found that 37% of known compounds met no hazard criteria, 24% were of concern/potential concern, and 39% had insufficient research. There is a concern that these unknown additives may enter the food chain or freshwater bodies. There is also an increasing discovery of additives, such as phthalates, which act as endocrine disruptors.

BDM additives of high concern must be replaced with safe alternatives. Chemicals should also be thoroughly assessed before being put into any environment.

Carbon-rich mulches such as straws, hay and sticks can also cause too much moisture. Furthermore, there is also the potential of nitrogen immobilization due to microbes utilizing nitrogen to decompose carbon-rich mulches. Paper mulches, however, decompose too fast.

Additionally, there aren't good laws for biodegradable mulches either. The most strict standard is the EN 17033, a European standard used for biodegradable mulches. It is the most rigorous evaluation, but even this standard falls short as it doesn't take into account substances or additives that are underresearched. This indicated that even the "best" mulches may pose threats to soil quality, crop yield and human health.

Fruit pomace and crustacean is a byproduct of fruit processing and despite being rich in polysaccharides, it is often wasted. According to the food and agriculture organisation of the UN, 130 million tons of food are wasted each year. This includes processing byproducts such as fruit pomace. However, this waste contains valuable biopolymers that can be applied to replace petroleum-based plastics as an eco-friendly, biodegradable solution.

Pectin has been a biopolymer of focus and it is abundantly present in fruit pomace. But alone, it doesn't have good mechanical strength. So, scientists are experimenting by creating compound substances with pectin and other biopolymers. Chitosan, another common biopolymer in food waste, is excellent in film forming.

Classification of Polysaccharides

Pectic Polysaccharides	Pectin forms the primary component of plant cells. It can form gels and films. It is known to be biocompatible and has tunable barrier properties.
Cellulose derivatives.	It is the most abundant renewable resource. Natural cellulose is difficult to dissolve and process. Nanocellulose can increase tensile strength and oxygen barrier properties. It is also hydrophilic.
Chitin-derivatives	Chitin is extracted from shrimp, crab shells and insect exoskeletons (crustaceans). It is the second most abundant biopolymer. A limitation is that it takes lots of energy to form.

Fruit pomace polysaccharide extraction:

- Physical methods are known to be environmentally friendly and efficient. Examples include:
    - Ultrasonic-assisted extraction (UAE) disrupts cell walls with intense mechanical shear forces and turbulent effects.
    - Microwave-assisted extraction (MAE) uses dipole radiation and ionic conduction of polar molecules, generating rapid volumetric heating.
- Biological methods include:
    - Using enzymes provides extremely reliable technical support for efficient pomace extraction.
    - The barrier of enzyme utilisation is:
        - Cost
        - Optimization in efficiency parameters:
            - Enzyme hydrolysis process
            - Fermentation process
            - Technology integration
- Novel solvent systems
    - They open a path-way for green extraction.
    - Novel solvents include deep eutectic solutions
    - Future research can look into:
        - Precise design of DES structures for tailors solvents for specific polysaccharides
        - Creating hybrid techniques with physical or biological techniques.

Film forming methods:

1. Solution casting: produces uniform films with solution casting and volatilization drying
2. Extrusion blowing: where molten biopolymers are shaped through blowing air.
3. 3-D printing technology
4. Electrospinning: the formation of a fibre with an applied electric current.
5. Layer-by-layer assembly (LBL): this technique involves alternating deposition of oppositely charged polysaccharide molecules.

To enhance films, blending technology has become a crucial method for preparing polysaccharide-based films. Multicrossliking helps to improve mechanical properties, biocompatibility, and degradability. Incorporating nanomaterials such as cellulose nanofibres and metal-oxide nanoparticles can improve mechanical properties as well as barrier and functional characteristics. Cross-linking modification involves adding chemicals, heat, or light to make long chains of sugar bond together, This process also creates strong films.

Biopolymers are increasingly being studied for their possibility to become a biodegradable replacement to traditional plastics. A polymer is a macromolecule made of repeated units known as monomers. Biopolymers are natural polymers derived from living organisms. Examples include’ DNA, RNA, proteins, cellulose, chitin, scratch, and more. As a renewable resource, it prevents the exploitation of fossil fuels and provides a way to reduce the negative impacts on Earth. However, the adoption of biopolymers has remained relatively scarce due to some barriers:

1. They are brittle, being prone to cracking and breaking,
2. Instability in heat.
3. High permeability to water vapour and oxygen.
4. Low melt strength

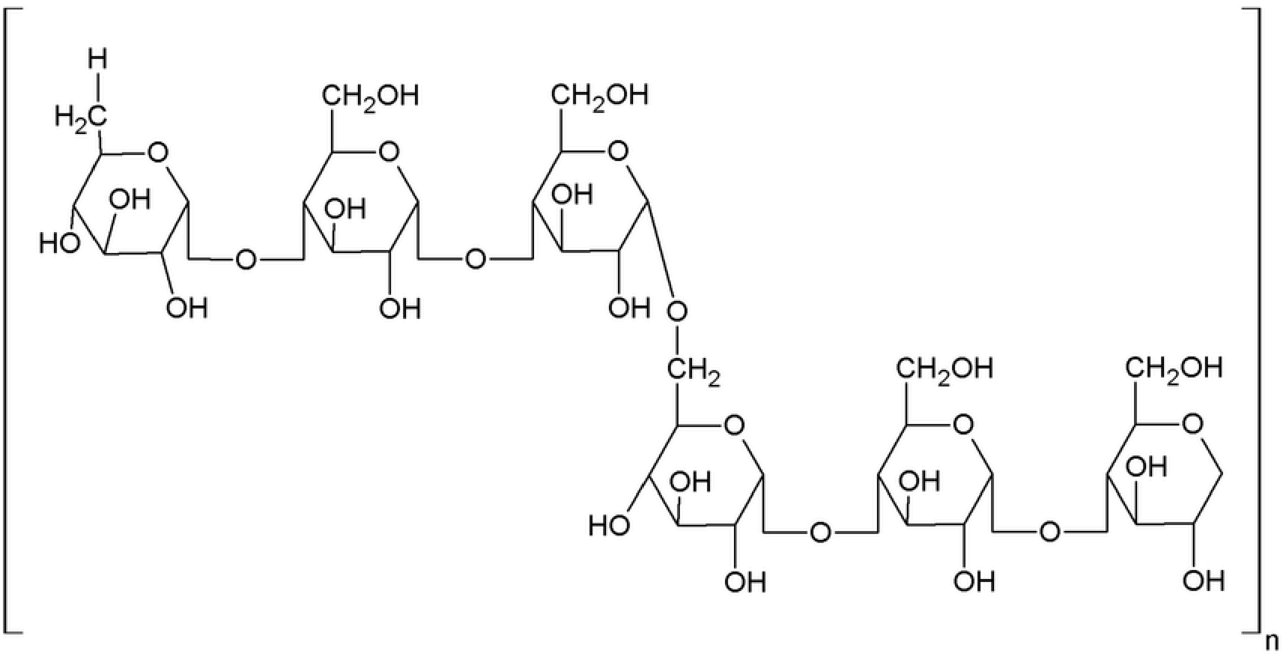
Common biopolymers include:

Polylactic acid (PLA)	It is the most commonly used biopolymer. They are compostable in industrial settings and have high mechanical strength, low toxicity, are resistant to wear and tear and stable under UV. It is also gas and vapour-permeable.
Polyhydroxyalkanoates (PHA)	It is produced by microorganisms and is sustainable for food packaging. However, they have a high cost.
Polybutylene Adipate terephthalate	They are flexible and permeable, but they need to be composted in an industrial setting.
Polycaprolactone (PCL)	They are hydrophobic and have a low melting point. Its properties can also be enhanced with coatings.

Pollulan

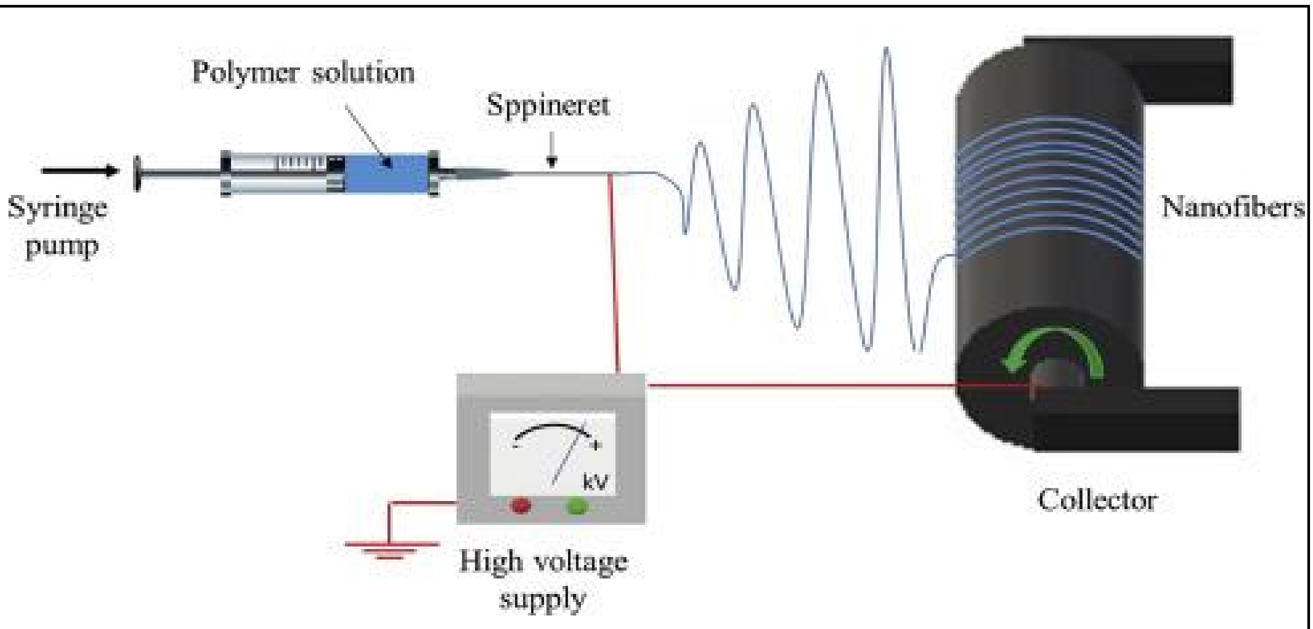
Pullulan is a polysaccharide made of maltotiose units. It is produced with a simple fermentation process involving fermentation with certain feedstock made with sugars. Pullulan can also be made to be partially or fully soluble in water or even insoluble. This can easily be chemically altered. Pullulan can also be used as a flocculent. Pollulan exhibits oxygen barrier properties, acting similarly to polystyrene (styrofoam).

Pollulan is a tasteless, odourless, white powder. As it is slowly dissolved in the human body, pollulan should be taken in small amounts.

Pullulan Structure	

Electrospinning

Electrospinning is a voltage-driven electric fabrication process. It is a phenomenon where nanofibres are created from a polymer solution.

Basic Electro-Spinning Setup	 Source

Effects of Solution Parameters

Viscosity	Higher viscosity encourages polymer chain entanglements. Lower viscosity causes electrospraying.
Conductivity	Solutions with higher conductivity create bead-free formulas. It is important to assess the impacts of additives on conductivity.
Solvent Selection	The solvent should completely evaporate during the electrospinning process. A solvent with too low a boiling point can clog the needle. A solvent with low vapour pressure can be selected. Fibre diameter can also be lowered with solvents with lower boiling point. Low conductivity, resulting in a higher diameter. The opposite relation applies for vapour pressure/dielectric constant.

The spinning process begins when an electrical field is created between the needle and the collector. The positive voltage is applied to the needle, and the negative voltage is applied to the collector. The closer the needle is to the collector, the less time the solvent has to evaporate. So, though the distance must be balanced, the nature of the electrospinning device can help with binding. The flow rate must remain stable to maintain Taylor's cone. The flow rate also impacts deposition density (slow means thicker, fast means thinner) and fibre size. Blunt needles are typically used, but in general, the more viscous the solution is, the more blunt the needle should be. The collector also influences the final product. A flat plate results in randomly placed fibres, and a rotating drum results in random or aligned products. There are also more options for specific applications. Furthermore, people may also choose conductive metal for the collection substrate or even a compound substrate for easier removal.

The environment also impacts humidity, which in turn impacts viscosity, solvent evaporation and fibre quality. Air flow improves solvent evaporation and prevents defects. Gas-assisted/hot air spinning can reduce clogging and stabilise clogging. Blow spinning is also emerging as an alternate method for electrospinning.

Solution blow spinning (SBS) is a portable and conformational device. It allows for fibre formation or deposition on many substrates. There are also far fewer essential guidelines. SBS fibres are more porous but electrospinning offers greater tensile strength due to creating low fibre diameters. Also, SBS fibres have fewer fibre bundles.

Alginate

Alginate is a biomaterial being applied in a variety of fields including wound healing, tissue engineering, drug delivery, and various hydrogel applications. Derived from brown seaweed, it is known for its biocompatibility, low toxicity, and relatively low cost. It also offers mild gelation after the addition of the cation, Ca^2+ (calcium ion). It is extracted by treatment with aqueous alkali solutions, commonly NaOH. The extract is filtered and either sodium or calcium chloride is added to precipitate alginate. Alginate salt can be transformed into alginate acid by adding dilute HCI. After purification and conversion, water-soluble alginate powder is formed.

Alginate is degraded by the enzyme, alginase. Alginate gels (hydrogels) have very limited mechanical stiffness on their own so it is common to include other compounds such as nanoparticles for mechanical strength.

Sodium alginate can be a strong adhesive for metals but it must be dry and cover the whole surface area. Adhesion is stronger after drying, in this study, it was stronger at 48hrs rather than 6-24 hours. Alginate bonds are strong even in high temperatures but bonds weaken upon exposure to water. Light sanding the surface is essential for strong adhesion.

Sodium alginate also performed better than other biopolymers and similarly to standard metal adhesives. Other biopolymers are also water soluble and their bonds weaken upon contact with water.

Cellulose

Cellulose is the most abundant biodegradable polymer. It can be derived from renewable and even waste sources. Cellulose has been getting immense recognition due to their excellent potential in wound dressing, filtration and clothing. Cellulose faces challenges into being electrospun as there are not many solvents that can be used with this substances.

Cellulose is a carbon rich material. Cellulose can be extracted from paper such as old newspaper or office waste paper. This is done by removing all undesired elements such as ink or contaminants. Cellulose is separated from paper pulp through floatation or washing. Deinking agents are then used for further purification. Cellulose may also be extracted from waste fabric. Other sources of cellulose include pineapple leaves and carrot peels.

Pectin

Pectin, found in almost all plants, contributes to the cell structure. Pectin is a high-molecular weight carbohydrate polymer. The name pectin originates from a Greek word, ‘pektos,’ meaning firm and hard, showcasing pectin’s ability to form gels.

Pectin is especially found in the rinds of citrus fruits and apples. It is a gelling agent, contributing to the solidification of jams.

Vegetable Glycerin

Vegetable glycerin or glycerol is a clear liquid commonly made of soybean, coconut, or palm oils. It is odorless and sweet-tasting, often used as a sweetener, preventing excessive blood sugar. Vegetable glycerin is also used in the cosmetic industry, able to moisturise the skin. Furthermore, vegetable glycerin can provide a strengthened gut.

Vegetable glycerin is obtained from plant oils. It is believed to be discovered by accident when a mixture of olive oil and lead monoxide was heated. However, it became economically significant after its application in dynamite in the 1800s. Vegetable glycerin is made by heating triglyceride-rich vegetable fats (such as palm and coconut oils) under pressure or with a strong alkali. In this reaction, glycerin is split away from the fatty acids and is mixed with oil, forming the odorless, slightly sweet liquid we know today.

Glycerin has many benefits and applications. It is said to improve skin moisture and reduce constipation. It may also boost hydration and, in turn, athletic performance. However, with excessive amounts, it can lead to headaches, dizziness, diarrhea, and vomiting. Also, some may face allergic reactions to vegetable glycerin as well.

Extracting Materials Through Waste

Purpose	Material	Method
Film-forming	Pectin	Pectin can be extracted from citrus peels using the following method: 1. Prepare the apple pomace powder (10g) 2. Mix 500 mL water with 10 g orange peel powder 3. Add citric acid/water solution adjusted to a pH of 2 a. Stir well, ensuring all peels are covered. 4. Place the beaker in an 80 degrees celsius hot water bath for 90 minutes 5. Strain the solids using a muslin cloth 6. Precipitate the pectin from the remaining liquid using 99% isopropyl alcohol a. Collect the gel-like clumps 7. Dry and crush the remaining pectin a. Dry the pectin at 50 degrees celsius
Reinforcement	Cellulose	Paper is already mostly cellulose, using simple purification methods using a weak acid, we gain cellulose using this method: 1. Shred Paper. 2. Boil paper with baking soda and water (1 tsp baking soda with enough water to cover the paper, 45 minutes). 3. Pour all contents into a strainer and drain the paper. 4. Rinse pulp. 5. Blend pulp with 1.5 cups of fresh water.
Film-forming	Startch	Extracted from potato peels.
Cross-linking	Calcium Acetate	Calcium acetate is derived from eggshells and acetic acid, following this process: 1. Membranes are removed from eggshells and they are crushed into a fine powder using a blender. 2. 10g of eggshells is mixed with 100 mL of 5% acetic acid. 3. Wait 48 hours, or until the reaction is complete. 4. Filter solids with a coffee filter to be left with a

		solution of calcium acetate.
Plasticizer	NADES substance	Sugar syrup and glycerin.
Hydrophobic layer	Beeswax and pectin	Add 1.5 tsp of beeswax to a pectin and water solution. Dip the film in the solution and wipe off the excess beeswax.

What are NADES?

Deep Eutectic Solvents (DESs) are a eutectic mixture (substances with two or more components with the lowest possible melting point) composed of a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA) combined at a defined molar ratio. Typically, Natural Deep Eutectic Solvents are aqueous mixtures of HBAs and HBDs obtained from natural sources. This makes NADES more environmentally friendly than traditional organic solvents. Examples of HBAs and HBDs are listed in the table below:

HBA	HBD
Choline chloride (ChCl)	Amino acids
Organic ammonium	Polyols
Fatty acid (can act as both in some cases)	Organic acids
Alcohol → using glycerin in a NADES substance will reduce the required amount of glycerin, making the film cheaper	Sugars → glucose/fructose from pineapple peels
Citric acid → adding it here will make it so that I don't have to add it anywhere else	

NADESs are known for their ease of preparation. They can be made by heating/stirring or grinding compounds until a clear liquid is produced. This can also be done by combining, dissolving in water, and freeze drying. They also have adjustable properties, having variable components. NADES may be used to extract bioactive compounds from agri-food and marine biomass.

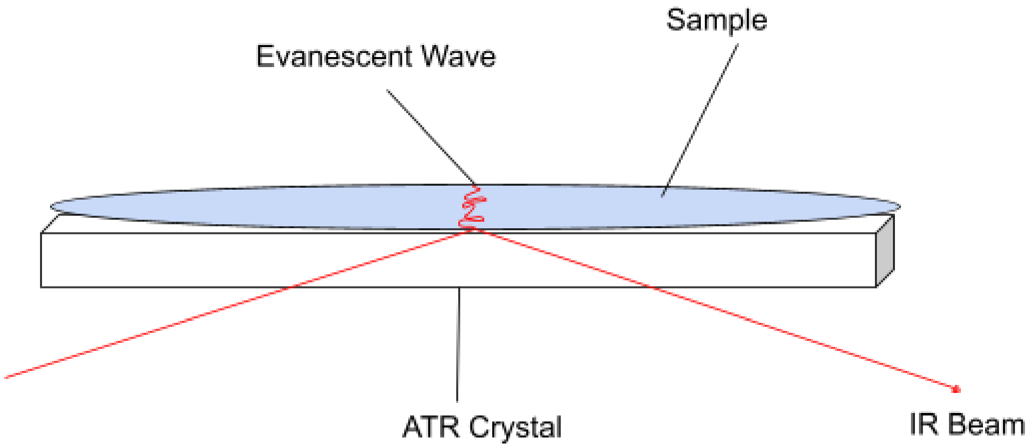
NADESs are advantageous for biopolymer-based films due to their biocompatibility and biodegradability. They have excellent solubility with polysaccharides. Being able to adjust the degree and bonding of hydrogen films, the application of NADESs can create a plasticizing effect. For example, in a chitosan-based film, though the addition of NADESs did reduce stiffness and tensile strength, attributes such as flexibility and water barrier properties improved. To improve water resistance when using hydrophilic NADESs, composite films using hydrophobic materials can be made. The addition of bioactive ingredients such as polyphenol from pomegranate peels can also benefit the soil.

Sugar and Sugar-Alcohol Eutectic Mixtures

NADES are often diluted in water, these types of NADES should be described as ternary NADES. When substances are hydrated, the eutectic ratio may not be maintained. A common NADES ratio of choline chloride and glycerol is 1:2. Glycerol to glucose ratios are often 2:1.

What is FTIR-ATR?

Fourier Transform Infrared Spectroscopy (FTIR) is an analytical chemistry method which works by determining what functional groups are present through the vibration of molecules after being exposed to infrared light. Attenuated total reflection (ATR) is a sampling technique that allows one to analyse samples directly in a liquid or solid state, reducing sample preparation. ATR works by sending an infrared wave at a particular angle onto the crystal. Then, the light bounces and creates evanescent waves. Molecules within the sample absorb certain frequencies of these waves and this information is carried out to the other side.



Method

Section 1: Parameters to Assess

Two main objectives were defined:

Objective #1	Objective #2
Minimizing harmful leachates	Similar effectiveness to commercially available biodegradable films

In objective 1, the goal is to create a film that minimizes harmful leachates entering the soil. The performance in this aspect will be measured using bioassay analysis on seed germination. This will be done by the following steps:

1. **Leachate Extraction**
    1. Purpose: Attain leachates front the film for evaluation
    2. Method: the developed film as well as the conventional biodegradable and plastic mulch will be kept in deionized water for 24 hours, leaving a leachate solution.
2. **Leachate Testing**
    1. Purpose: Set up tests to determine the toxicity of the mulch film's leachates.
    2. Method: The leachate solution will be added to a paper towel with mustard seeds inside.
3. **Leachate Toxicity Analysis**
    1. Purpose: Analyse impacts on biological factors.
    2. Method: The rate of germination of each seed will be analysed.

In objective 2, the goal is to create a film that performs as similarly as possible to commercially available biodegradable and plastic mulch films. The performance in this aspect will be measured through mechanical & physical properties, cost, durability, and weed suppression. The developed biodegradable film will be considered successful if its measured "effectiveness" meet or exceed those of commercially available plastic and biodegradable mulch films, or fall within a maximum deviation of 10% where trade-offs are necessary. This will be done by the following steps:

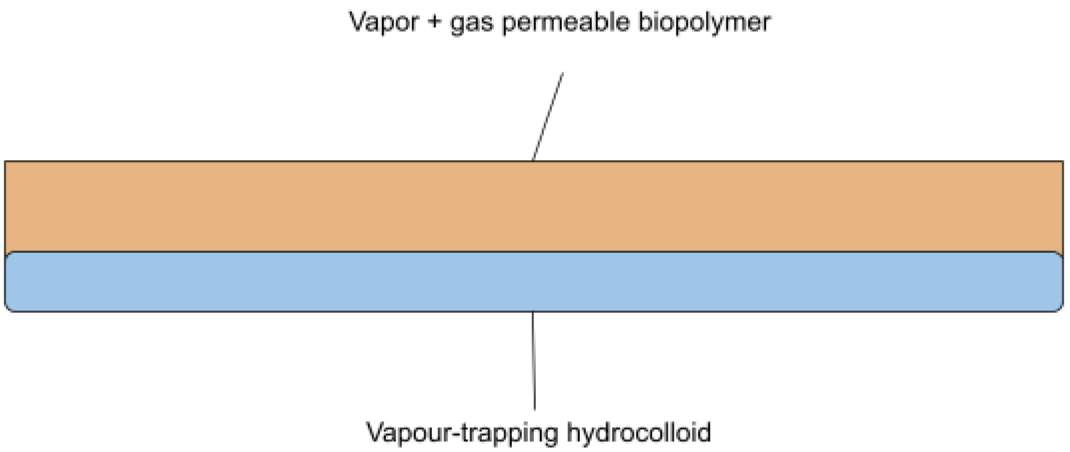
1. **Physical Properties**
    1. Light Transmittance (Optical Transparency) Test
        1. Purpose: Measure how much light passes through the film.
        2. Method: The amount of light passing through the film will be measured using a phone lux meter and compared to ambient light without the film (percentage of light transmission).
    2. Thickness Measurement
        1. Purpose: Determine film thickness.
        2. Method: Thickness will be measured using a ruler at multiple points and averaged.
    3. Mass per Unit Area (Grammage Measurement)
        1. Purpose**:** Measure material usage per area.
        2. Method: Film mass will be measured using a weighing scale, and area will be estimated to determine mass per unit area (g/cm^2).
    4. Bulk Density Estimation
        1. Purpose: Estimate material compactness.
        2. Method: Density is calculated by dividing mass by estimated volume (thickness × area).
    5. Water Permeability (Short-Term Water Transmission Test)
        1. Purpose: Assess water permeability.
        2. Method: A fixed volume of water (10 mL) is placed on the film, and the amount of water transmitted through the film in 60 seconds is measured.
2. **Mechanical Properties**
    1. Flexibility / Elongation Under Load Test
        1. Purpose: Evaluate film flexibility.

        ii. Method: The amount of stretching under 2kg of force will be measured.
    b. Tensile Strength (Breaking Load) Test
        i. Purpose: Measure resistance to pulling forces.
        ii. Method: The amount of weight required to cause the film to break will be measured.
    c. Stiffness (Bending Angle Test)
        i. Purpose: Assess resistance to bending.
        ii. Method: The overhang length required to bend a 2 cm x 8 cm section of the film to a 45-degree angle is measured.
    d. Tear Resistance Test
        i. Purpose: Measure resistance to tearing once a tear is started (tear propagation).
        ii. Method: The weight required to continue a tear.
    e. Puncture Resistance Test
        i. Purpose: Assess resistance to puncture.
        ii. Method: The weight required to puncture the film is measured.

3. **Durability**
    a. UV Exposure Stability Test
        i. Purpose: Assess resistance to ultraviolet degradation.
        ii. Method: Films will be exposed to a UV source for 24 hours. The films will be visually and mechanically evaluated.
    b. Thermal Stability Test
        i. Purpose: Assess resistance to temperature extremes.
        ii. Method: Films are exposed to hot and cold conditions for 24 hours. The films will be visually and mechanically evaluated.
4. **Cost**
    a. Material Cost Analysis
        i. Purpose: Estimate economic feasibility, indicator of applicability.
        ii. Method: Cost of raw materials will be calculated. Manufacturing costs will not be included as it can vary significantly due to variability in industrial processes.
5. **Weed suppression**
    a. Bioassay
        i. Purpose: Evaluate effectiveness in preventing weeds.
        ii. Method: Films are applied to soil, and time to weed germination and growth is compared across treatments.

In summary, the developed film should not only have negligible leachate toxicity but also perform similarly to traditional PE (polyethylene) mulch films.

Section 2: Phase 1: Initial Prototype Development (Baseline Prototype)

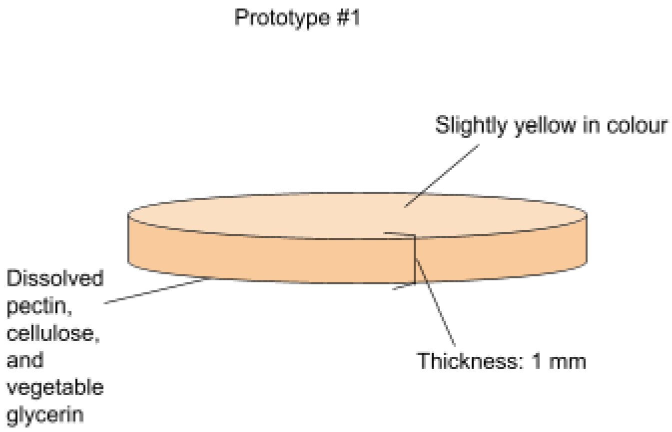


Above is a proposed design for the BDM. Many biopolymers are vapour and gas-permeable. Although gas permeability is important for soil aeration and microbes, vapour and condensation should be trapped for the plants. So, the plan is to create a bi-layer mulch film with a biopolymer layer on top and a hydrocolloid layer below to trap vapour.

Unfortunately, due to the inability to access an electrospinning apparatus, the design was changed in order to work with the method of solution casting. In order to have a basis on which to design the film, a simple biopolymer film was created. This film was made of cellulose, pectin, and glycerin. The only aspect varying from each film was the amount of glycerin (amounts of glycerin are: ¼ tsp, ½ tsp, and ¾ tsp). Below are daily observations from the film creation.

Phase 1-1

Design



The film will be created with cellulose, pectin, and glycerin. This film will definitely not fulfil all requirements. However, it will serve as a basis to design better films. The plan is to evaluate the physical and chemical properties of the preliminary pectin/cellulose film.

Pectin and cellulose were chosen as they are both easily accessible. Being one of the most commonly wasted biopolymers, using pectin can provide a unique “waste management” aspect to this film. Vegetable glycerin will serve as a safe, natural plasticizer.

The film will be created using the solution casting method. The biopolymer solution will be poured on an aluminum foil lined yogurt lid. Then, it will be completely dried over 48 hours.

Predictions for the preliminary film:

1. I expect it will have a jelly-like texture.
2. It will not be as strong as the LDPE film.
3. It will be clear in colour.
4. It will be thicker than the LDPE film.
5. The film will be uniform with minimal or no holes.

Observations

Qualitative Observations

While Making The Film	- Changed the amount of glycerin in each film to observe differences, adding ¼ tsp glycerin more in each film - The water must be at 70-80 degrees celsius to easily dissolve the film  - The solution smells “woody” - Pectin easily formed clumps and has a fibre-like appearance  - Heating helps to accelerate to dissolving of the pectin - The film with the most glycerin was the least viscous - The solution was slippery to touch - The solution was stirred using a wooden stick - First casted film

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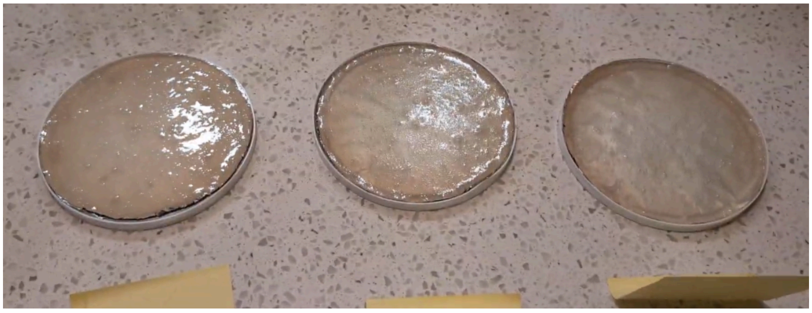
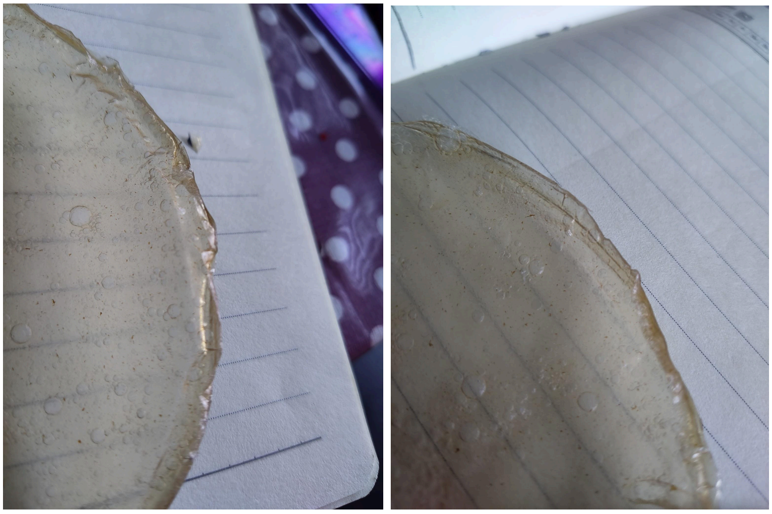
<tr><td></td><td>
- Immediately upon casting the solution:
</td></tr>
<tr><td>Day 1</td><td>- ¾ tsp glycerin
  - Visible pectin clumps.
  - Uniformly dry but gel-like.
  - Pectin clumps are visible.
  - More “jelly-like” on the right side.
  - Most wet out of all films.
- ½ tsp glycerin
  - Uniformly dry
  - Less gel-like than ¾ tsp glycerin film.
  - More jelly-like on the bottom right side.
  - Most clear out of all films.
- ¼ tsp glycerin
  - Hard on the center.
  - Dryness is not uniform.
    - The middle is less dry.
  - The right edge is the most jelly-like.
  - Almost completely dry.</td></tr>
<tr><td>Day 2</td><td>- ¾ tsp glycerin
  - Still completely wet.
    - Dried after 15 more hours.
  - Peeled easily once dry.
- ½ tsp glycerin
  - Became thinner as the film dried.
  - Sides are starting to peel off the yogurt lid plate.
  - Not fully dry.
    - Dried after 7 more hours.
  - Peeled easily once dry
- ¼ tsp glycerin
  - So dry that it came off the plate
    - Peeled off very strong and flexible</td></tr>
</table>

	- Upon first impressions, all films seem to have similar properties including similar flexibility and strength. - Pictures showing the brittle sides: 
During Testing	- Thickness - Sides are very dry and brittle. - May become a problem as when a tear is started, it is easy to break. - In the case of the ¾ film, the sides were not as brittle as they seemed to be thicker, merging with the film. - Lux - Lux measurement was confusing as it fluctuates from place to place. However, lux was measured in the place with the most lighting. - Mass - Had to estimate as there wasn't access to a scale. Used the weight of a coin to compare. - Area - The area of all films are the same - Permeability - This test will be done before other tests as it will show how the film will perform when wet (after being impacted by irrigation and rain). - The film became “jelly-like” where the film touched. - Stiffness - It is able to bend without breaking but the film does not “drape” as it should. - Flexibility - The films do not stretch at all.

	
	- Tear Resistance
	    - The amount of weight required to continue the tear was measured using a binder clip and a “ziploc” bag.
	- Puncture Resistance
	    - The amount of weight required to puncture the film was measured using a sharp object, seeing how many coins it took to puncture the film.
	- Solution casting on a surface with irregular sides leaves the sides brittle.
	- The film gets weak after getting wet.
	- There are air bubbles but they don’t seem to cause many problems.

Quantitative Observations

	Thickness	**Lux passing through**	**Mass**	**Area**	**mass/area**	**Density**	**Permeability**	**Stiffness**	**Flexibility**	**Tear resistance**	**Puncture resistance**
1/4	1 mm	1092	2 g	95.03 cm^2	0.21 g/cm^2	0.0021 g/cm^3	0.1 mL	5 cm	1 lbs	40.11 g	182.08 g
2/4	1 mm	1129	2 g	95.03 cm^2	0.21 g/cm^2	0.0021 g/cm^3	0 mL	4 cm	3 lbs	25.27 g	108.05 g
3/4	1 mm	1267	2 g	95.03 cm^2	0.21 g/cm^2	0.0021 g/cm^3	0 mL	3 cm	5 lbs	26.59 g	194.90 g

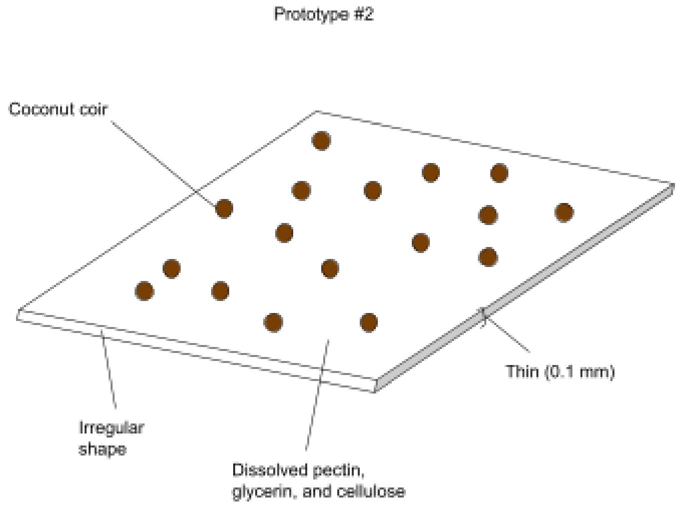
Future Improvements

The biopolymer film performed very well. It was comparable in many aspects to LDPE mulching. For example, it had strong tensile strength requiring up to 5 lbs of force for failure. However, some downsides were still observed. Below, are weaknesses to the film and the potential improvement:

1. Brittle sides
    a. To address this, the film will be casted on a flat surface (parchment paper).
2. Waterproofing
    a. Address this using beeswax and coconut husk.
3. Tear Resistance
    a. Adding calcium for crosslinking.
    b. Adding coconut coir.
4. Flexibility
    a. Needs to be thinner (0.2 mm).
        i. Using roughly 33% less material over a larger surface area.

Phase 1-2

Design



The film will utilise the same biopolymers: cellulose and pectin. It will also use the same type of plasticizer. However, a few changes have been made from the previous film. Firstly, it will contain coconut coir for waterproofing and additional tear resistance. Furthermore, less material will be used. The new recipe to make a single film:

- ¼ cup water
- ¼ tsp glycerin
- ⅛ tsp cellulose
- ¼ tsp pectin
- ¼ tsp coconut coir fibres (finely shredded, method stated below).

Method to prepare coconut fibres:

1. Add coconut coir to warm water, soak for 15 minutes

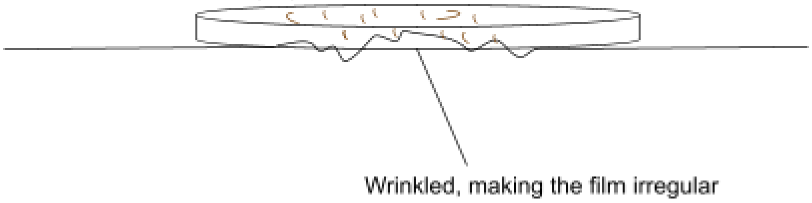
2. Air dry the coconut coir for 10 minutes
3. Separate remaining clumps and cut into small fibres (<4 mm)
4. Collect ¼ tsp coconut coir fibres for a single film

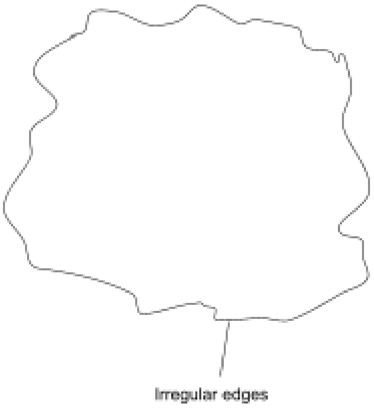
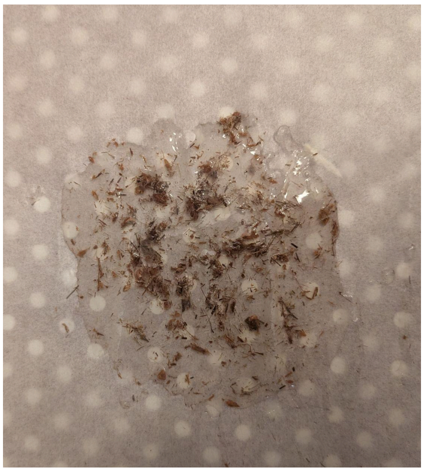
After coconut coir fibres are attained, it will be sprinkled over the freshly casted mulch film.

Finally, the last change is that the film will be cast upon a flat surface, parchment paper. This will likely reduce the thickness, making the film more flexible.

Observations

Qualitative

While Making The Film	- Tried adding calcium to the solution for potential strength but it did not work and ended up clumping. - The solution seemed to be less viscous than the other film, but this was not the case as it soon became thicker - The parchment paper began to wrinkle up when the solution touched the paper.  - Edges were very irregular, will not make a “perfect” shape

	  - Although there was a lot more area, the film did not spread much due to being extremely viscous. 
Day 1	- Films are still mostly wet. - Though the substance was thick at first, it got significantly thinner. - Coconut coir does not seem to reduce tear resistance. - The coconut coir simply seems to make holes in the film which is likely ineffective (may be useful for permeability)

Day 2	- Wanting to make the film more flexible, the film was made much thinner, making the film more brittle.
	- Upon first impressions, the coconut fibres seem to make the film more brittle rather than strong due to the small holes it made.
	- It is possible that crosslinking through calcium and citric acid may help.
	- Potential reasons for brittleness
	    - Too much pectin.
	    - Not enough plasticizer (glycerin)
	        - There needs to be up to 45% glycerin of the polymer's weight.
	- Crosslinking can potentially make the film stronger. A combination of ester and ionic crosslinking with citric acid and calcium acetate may be useful in future prototypes. Although, it is crucial to keep the concentration of the calcium low so as to not reduce soil fertility and deteriorate plant health.

During Testing

- Thickness
    - The film is much thinner than the previous prototype but this also made it more brittle.
- Lux
    - Coconut coir only blocked a small amount of light.
- Mass
    - All are likely 1 gram, being much lighter than the previous film.
- Area
    - The area of all films is difficult to calculate as it has irregular shape. However, estimation was used.
- Permeability
    - The holes that the coconut coir created resulted in higher permeability.
- Stiffness
    - It is able to bend without breaking but the film does not “drape” as it should. Also, it crumples much easier than the previous prototype.
- Flexibility
    - The films do not stretch at all.
- Tear Resistance
    - The amount of weight required to continue the tear was measured using a binder clip and a “ziploc” bag.
    - The film was not effective at tear resistance.
- Puncture Resistance
    - The amount of weight required to puncture the film was measured using a sharp object, seeing how many coins it took to puncture the film.
    - The film was also not effective at puncture resistance.
- It was slightly difficult to peel the film from the surface of the parchment paper. This was not due to adhesion to the surface, but rather, the brittleness of the film.
- The film was rough to touch and not uniform in thickness or shape.
- The coconut coir creates holes in the film and results in a weaker film. Furthermore, coconut coir is unable to degrade within 5-6 months.
- Unlike the previous prototype, this film was actually more clear in colour.

Quantitative

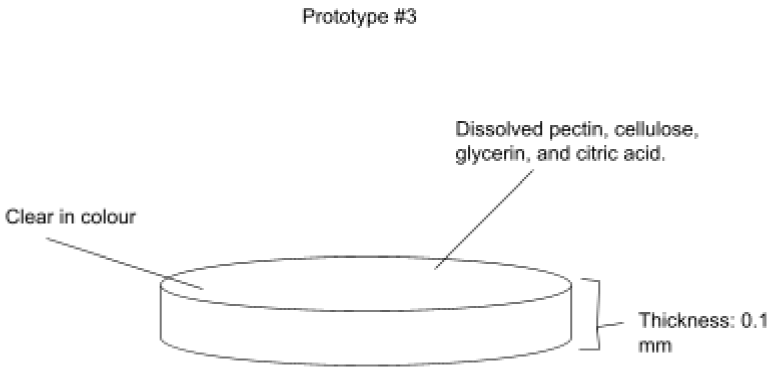
	Thickness	**Lux passing through**	**Mass**	**Area**	**mass/ area**	**Density**	**Permeability**	**Stiffness**	**Flexibility**	**Tear resistance**	**Puncture resistance**
1/4	0.1 mm		1 g	20 cm^2 (estimate)	0.05 g/cm^2	5 g/cm^3	0.5 mL	4 cm	0 lbs	8.8 g	4.4 g
2/4	0.1 mm		1 g	20 cm^2 (estimate)	0.05 g/cm^2	5 g/cm^3	5 mL	5.5 cm	0 lbs	4.4 g	4.4 g
3/4	0.1 mm		1 g	20 cm^2 (estimate)	0.05 g/cm^2	5 g/cm^3	0.5 mL	4 cm	0 lbs	22 g	4.4 g

Future Improvements
The biopolymer film performed worse. For example, it was brittle, low in flexibility, and stiff. There were also mistakes made in relation to the casting of the film. Below, are weaknesses to the film and the potential improvement:

5. Brittleness/lack of flexibility
    a. To address this, triple the amount of plasticizer (glycerin) will be added.
    b. Coconut coir will not be used for further prototypes.
6. Waterproofing
    a. To address this, crosslinking will be used.
7. Solution casting
    a. The film will be casted on the yogurt lid once again but to avoid brittle sides, aluminum foil will not be used. The lid will simply be oiled for ease of removal.

Phase 1-3

Design



For this film, the amount of glycerin was tripled. The new recipe is the following:

- ¼ tsp pectin
- ⅛ tsp methylcellulose
- ⅜ tsp glycerin
    - Tripled the amount from last time
- 1/16 tsp citric acid
- ½ cup water

Beyond the change in the amount of glycerin, all other factors were kept the same. I have also included citric acid for ester crosslinking. The film will be heated to create the bonds.

Observations
Qualitative

While Making The Film	- The film was extremely liquidy this time
	  - This is possibly because I may have added too much water from hydrating the cellulose
	- The film which was casted second was thickening the fastest
	- The film was cast on yogurt containers
	- The films look much clearer than previous attempts
	  - Does the aluminum foil cause a reaction to change the colour or the film?

Day 1	- Overnight, the film did get more viscous but it is still liquid. - The film is very uniform and clear. It has minimal air bubbles.

Day 2	- I tried to peel the film but it was not ready so I ended up ripping the film.
	- Also, I mixed vinegar and eggshells to make calcium acetate in order to do calcium crosslinking.
	  - The reaction will take at least 24 hours.
	  - I will have to stir it regularly.
	
	- Also, the films got thinner over time. Initially, they appeared to be much thicker.

12/26/2025	- Peeled all the films off but none came out smoothly. All of the films ended up sticking to the surface and the raised edges made it even more difficult to peel.
	    - Likely did not add enough oil.
	
	- Plastic (low-density polyethylene (LDPE)) films were attained.
	    - Observations:
	        - Both the developed and plastic films are similar in strength and flexibility but the developed film does not stretch as much.
	        - The plastic film is not completely clear so weed suppression will likely not be tested.
	- I need to make the film more flexible, leading me to fo for more plasticizer. However, since the film already feels tacky, this might be risky. If I continue to increase the amount of plasticizer in the film, it may end up tacky or weak.
	- Furthermore, the eggshell and vinegar reaction has stopped. This suggests that calcium acetate has formed.
	    - This allows for ionic crosslinking.

During Testing	- Observed problems with film #3:
	    1. It does not stretch enough.
	    2. It's still not waterproof enough.
	    3. Glycerin is expensive.
	- Potential solutions to address these concerns:
	    1. Using sorbitol instead of glycerin.
	    2. Using either lignin or a chitosan derivative for additional waterproofing.
	    3. Sorbitol derived from waste?
	What is the best waste-derived plasticizer?

	- Beeswax is also extremely expensive. A composite material using the natural waxes found on banana peels may be effective. - Furthermore, the wax coating needs to be minimal to still be hydrophilic enough to degrade within 6 months. Observations during testing: - Films are thin and flexible, but just a bit tacky. - They were put in the oven at 150 degrees fahrenheit for crosslinking and it seemingly worked. - The films are broken due to the strong adhesion of the biopolymers to the yogurt lid while drying. - Next time, I will use more oil. - While baking I saw the films actually started to stick to each other, indicating the potential of adhesion through heat. - Also, I noticed that the edges were curling as the film was baking.

Quantitative

	Thickness	**Lux passing through**	**Mass**	**Area**	**mass/area**	**Density**	**Permeability**	**Stiffness**	**Flexibility**	**Tear resistance**	**Puncture resistance**
1/4	0.1 mm		<1 g	103.87 cm^2 (estimate)	0.0096 g/cm^2	0.0963 g/cm^3	5 mL	3 cm	3 lbs	83 lbs	23 g
2/4	0.1 mm		<1 g	33.18 cm^2 (estimate)	0.0301 g/cm^2	0.3014 g/cm^3	6 mL	3.5 cm	0 lbs	145 lbs	33 g
3/4	0.1 mm		<1 g	86.6 cm^2 (estimate)	0.0115 g/cm^2	0.1155 g/cm^3	4 mL	3 cm	0 lbs	193 lbs	25 g

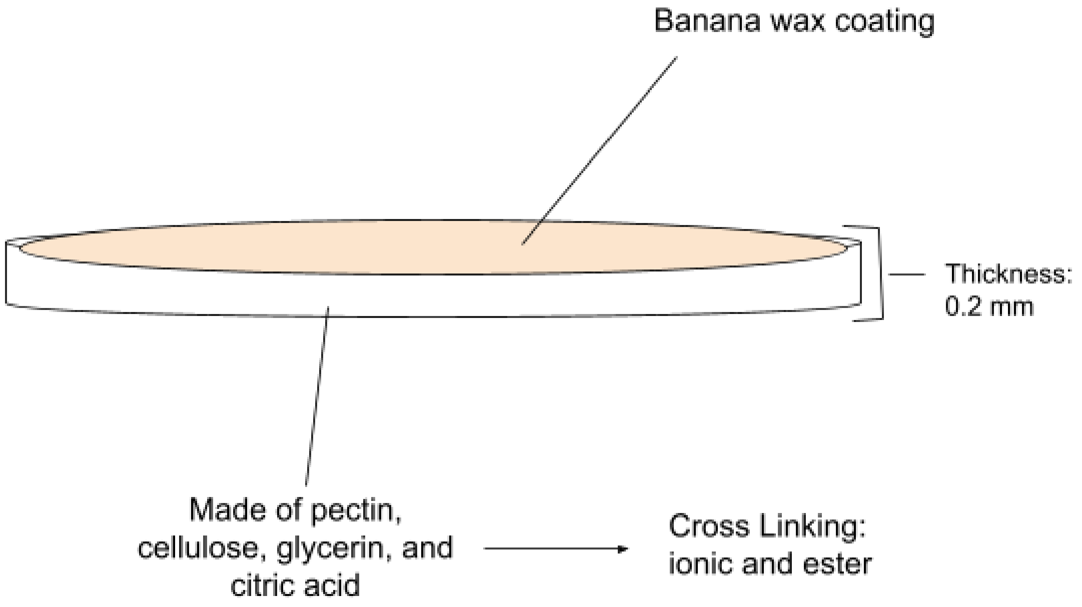
Future improvements

Though this film showcased significant improvement from the prototypes before, there were still some observed problems. These problems, and their potential solutions are expressed below:

1. It does not stretch enough: more glycerin will be added (double the amount).
2. It’s still not waterproof enough: a banana wax coating will be included and calcium crosslinking will be done.

Phase 1-4

Design



In this film, more glycerin will be used. A layer of banana wax will also be applied to the surface. Although the ratio of all ingredients increased by a factor of 2, the amount of glycerin was doubled to get more stretchy. The recipe for this film is:

- ½ tsp pectin
- ⅛ tsp methyl cellulose
- 1 ½ tsp glycerin
- ⅛ tsp citric acid
- Calcium acetate

Observations

Qualitative observations

While Making The Film	- Added double the amount of glycerin.
	- Film does not feel as slippery. Feels more like water.
	- Poured on new mickey mouse coasters
	    - With a strong surface tension, it is able to stay on the plate.
	- With the excess, I added it to the aluminum foil.
	    - Has a bit of a greyish tint so I don't think aluminum foil caused the original yellow colour.
	- 2 coasters have extra oil to reduce film adhesion.
	- Some are not a clean circle.
	- Although I did not notice much of a difference with citric acid, I added it.

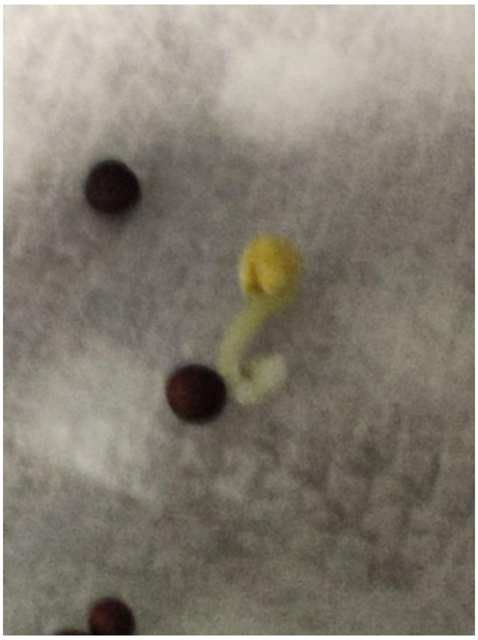
Day 1	- The films are drying → seems like they thinned a bit.
	- Also I put banana peels in acetone to extract the banana wax from the peels.
	- After the banana peels sat for a long time, some peels seemed more smooth.
	- Filter the acetone after soaking the banana peels for 60 minutes.
	  - Solution was orange
	  - Some solids still passed through after the coffee filters
	  - Same consistency (liquidy)
	  - Has an acetone smell
	
	Aluminum foil trial film:
	- Wanted to just observe the properties as a quick trial
	- It was hard to remove, also very thin and sticky, from the plasticizer. (Before crosslinking).
	- After crosslinking for 45 minutes, film was not sticky
	- Some are still soaking in calcium acetate
	  - Also, had to remake calcium acetate as it fell
	- Most films still feel tacky (not ready to remove yet).

Day 2	- Some films peeled but they broke. I found that I had to raise its edges all around to peel properly. - The “extra oil” films are still wet

	   
Day 3	- All films peeled. - I found that the thicker the film, the easier it is to peel. - Broken sides can still be pieces together with water.  

	
Day 4	- The last step was adding banana wax → little goes a long way. - The wax was a bit hard to apply. - All films are perfectly circle - Possibly more crosslinking would have helped for more strength.
During Testing	- The last step was adding banana wax → little goes a long way. - The wax was a bit hard to apply. - All films are perfectly circle, possibly more crosslinking would have helped. - Permeability was impressive, the banana wax made it more hydrophobic.

Bioassay	- Soak 2 cm x 2cm pieces of film in each cup of distilled water.
	    - Waiting 24 hours for the leachate solution to form.
	- Started the bioassay.
	- 20 seeds were placed in each piece of paper towel.
	- Each paper towel was soaked in either leachate solution or distilled water (control)
	- Each paper towel was kept in a ziploc bag
	    - Each ziploc bag was placed in a cool, dark drawer.
	
	- The seeds in the leachates seemed to grow much faster.

Quantitative Observations

	Thickness	**Mass**	**Area**	**mass/area**	**Density**	**Permeability**	**Stiffness**	**Flexibility**	**Tear resistance**	**Puncture resistance**
Trial 1	0.4 mm	2 g	70.9 cm^2 (estimate)	0.0096 g/cm^2	0.7052 g/cm^3	0 mL	4 cm	1 lbs	35 g	93 g
Trial 2	0.3 mm	2 g	78.5 cm^2 (estimate)	0.0301 g/cm^2	0.849g /cm^3	0 mL	6 cm	2 lbs	33 g	50 g
Trial 3	0.4 mm	2 g	70.9 cm^2 (estimate)	0.0115 g/cm^2	0.7052 g/cm^3	0 mL	4.5 cm	0.5 lbs	29 g	85 g
Average	0.367 mm	2 g	73.43 cm^2	0.0171 g/cm^2	0.7531 g/cm^3	0 mL	4.83 cm	1.17 lbs	32.33 g	76 g

Days	1	2	3	4	5	6	7
# of sprouted	0	0	0	0	0	0	0

seeds (Control #1)							
# of sprouted seeds (Control #2)	0	0	0	0	0	0	0
# of sprouted seeds (Control #3)	0	0	0	0	0	1	1
# of sprouted seeds (Leachate #1)	0	0	0	0	0	0	0
# of sprouted seeds (Leachate #2)	0	0	0	1	2	2	2
# of sprouted seeds (Leachate #3)	0	0	0	0	1	1	1

Days	1	2	3	4	5	6	7
% of sprouted seeds (Control #1)	0	0	0	0	0	0	0
% of sprouted seeds (Control #2)	0	0	0	0	0	0	0
% of sprouted seeds (Control	0	0	0	0	0	5	5

#3)							
Avg. % of sprouted seeds (control)	0	0	0	0	0	1.7	1.7
% of sprouted seeds (Leachate #1)	0	0	0	0	0	0	0
% of sprouted seeds (Leachate #2)	0	0	0	5	10	10	10
# of sprouted seeds (Leachate #3)	0	0	0	0	5	5	5
Avg. % of sprouted seeds (leachate)	0	0	0	1.7	5	5	5

Days	1	2	3	4	5	6	7
Avg. length of sprouted seeds (control 1)	0 mm	0 mm	0 mm	0 mm	0 mm	0.2 mm	0.25 mm
Avg. length of sprouted seeds (control 2)	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm
Avg. length of sprouted	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm

seeds (control 1)							
Avg. length of control seeds	0 mm	0 mm	0 mm	0 mm	0 mm	0.07 mm	0.08 mm
Avg. length of sprouted seeds (leachate 1)	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm	0 mm
Avg. length of sprouted seeds (leachate 2)	0 mm	0 mm	0 mm	0.2 mm	0.27 mm	0.43 mm	0.53 mm
Avg. length of sprouted seeds (leachate 3)	0 mm	0 mm	0 mm	0 mm	0.15 mm	0.21 mm	0.25 mm
Avg. length of leachate seeds	0 mm	0 mm	0 mm	0.07 mm	0.14 mm	0.21 mm	0.26 mm

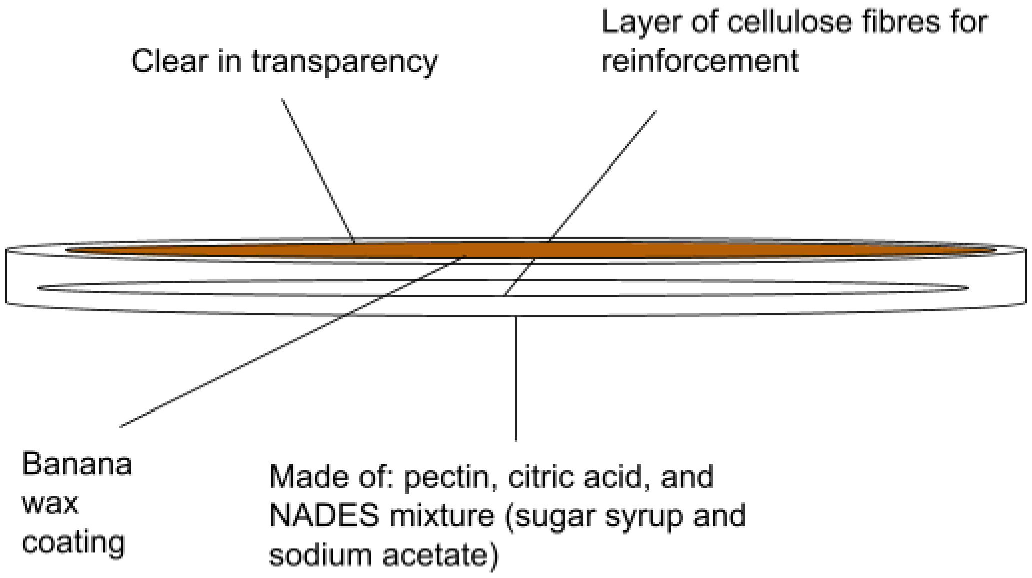
Future Improvements

Now, the film which is created is suitable and very comparable to plastic mulches. However, this film can still be improved by finding a way to more evenly coat the surface with the banana wax. Another barrier to worldwide application is cost. So, waste-derived biopolymers will be used to significantly reduce raw material cost.

Section 3: Phase 2: Exploratory Prototype Development (Waste-derived materials)

Phase 2-1

Design



The previous film was effective yet it did not meet needs for cost, being much more expensive than traditional LDPE films. Biopolymers are commonly found everywhere. Hence, they can easily be extracted from waste sources and this reduces the raw material cost of the film significantly. However, the cost of the plasticizer (glycerin), especially increases the cost. To reduce the plasticizer cost, a NADES-like substance will be used to make the film more flexible. In summary, this prototype will be created using waste materials to reduce the cost of the film. The extracts and their sources are listed in the table below:

Film former: pectin ⟶ citrus peels
Reinforcement: cellulose ⟶ recycled paper
Reinforcement: wax ⟶ banana peels
Plasticizer: NADES ⟶ sugar syrup from banana peels and sodium acetate from acetic acid and sodium bicarbonate (1:1 molar ratio) *Note: vinegar and baking soda is not a form of waste.*
Crosslinking: calcium acetate → eggshells and acetic acid *Note: vinegar and baking soda is not a form of waste.*

Observations
Qualitative

While Making	- Originally, I tried to extract pectin from apple pomace but the yield

The Film	was very low. Instead, I extracted pectin from orange peels.    - This worked well. It took roughly three days for the pectin to dry

	completely. In the end, there was less than 1 gram of pectin left. - The film was made the same way with the same formula. - The plasticizer for this film was a NADES substance made of sodium acetate and sugar syrup from banana peels.  - The cellulose was extracted from paper through a mild alkaline treatment to reduce impuritites. - However, since there was a lower amount of pectin, all amounts were brought down to match the original concentrations. - There was a strong orange smell which was not observed when creating the film with manufactured pectin. - The solution had a more liquidy feeling, it did not feel as slimy as the final prototype in the previous phase. - As per the design, the layer of cellulose was added to the top of the casted solution. However, the cellulose just ended up absorbing most of the solution and it did not turn out well.
Day 1	- The film continued to dry. - The film was more brown and tacky than other films. There was not much of the solution left on the casting surface.
Day 2	- - In the end, the film dried but the film was not even peelable. - Furthermore, it did not smell nice and it looked even worse.
During Testing	- The film could not be tested as it was not peelable.

Quantitative → No quantitative data

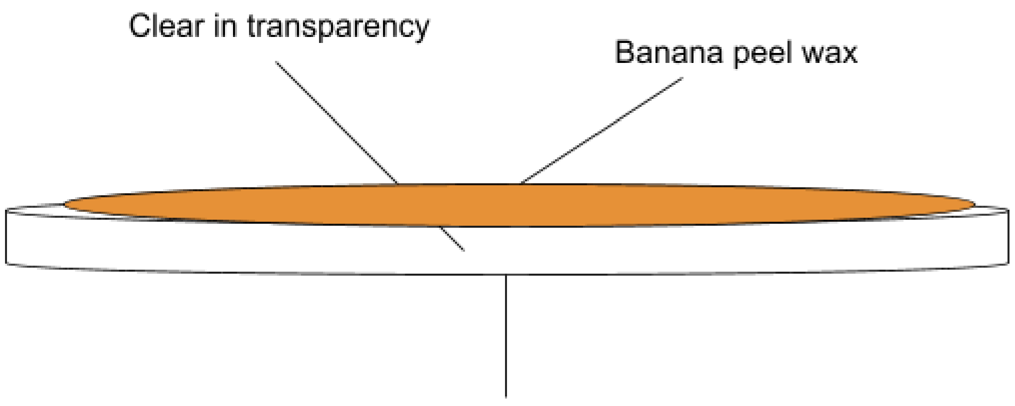
Future Improvements

The film was not even peelable. So, there are many improvements that need to happen.

1. Using a lower concentration of plasticizer so that it does not adhere to the casting surface, creating a peelable film.
2. Blending the cellulose into a micro-cellulose-like suspension instead of having a layer of cellulose on top.
3. Changing the NADES mixture as there was still crystallisation with the chosen HBA and HBD. Furthermore, it did not have a pleasant odour.

Phase 2-2

Design



Made of: cellulose, pectin, citric acid, and NADES mixture (sugar syrup and glycerin)

↓

The cellulose will be blended until it reaches a microcellulose-like texture.

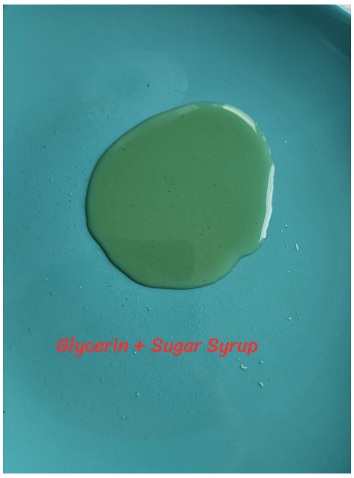
Film former: pectin ⟶ citrus peels
Reinforcement: cellulose ⟶ recycled paper
Reinforcement: wax ⟶ banana peels
Plasticizer: NADES ⟶ sugar syrup from pineapple peels and glycerin (1:2 molar ratio) *Note: glycerin is not a form of waste.*
Crosslinking: calcium acetate → eggshells and acetic acid *Note: vinegar and baking soda is not a form of waste.*

Observations

Qualitative

While Making The Film	- Extracted pectin from orange peels once again. - This time, the cellulose was blended (1% solution) with water on high for 20 minutes (intermittent). In the end, a suspension with fine cellulose particles was attained.

- Interesting observation:
    - When originally, it was attempted to extract banana peel sugars it did not work well. However, as the extract was boiled down, there was leftover wax on the pot which was scraped off and used for the film. There was no need to use acetone as a solvent to extract the banana peel wax.
- This time, the NADES mixture was made of glycerin and a sugars syrup. It was made by using pineapple peel extracts which contain a variety of sugars that are capable of making NADES. The ratio, based on previous literature, was a ratio of 2:1.
    - This created a much better plasticizer.

	 - - While casting the film, a few millimetres of the cellulose suspension was added before the dried orange peel pectin. Finally, the NADES was added. Once dry, banana peel wax would be rubbed on the surface. - The pectin took much longer to dissolve than the industrial pectin. - However, the film was less “slimy” than prototypes in phase 1, which means the pectin concentration may be too low.
Day 1	- While drying, it was noticed that the film was getting extremely thin. - This was worrying as this meant the film would not be as easily peelable.
Day 2	- Once dry, the film was peeled. - However, while peeling the film it was almost instantly evident there was too much plasticizer. The film was sticky and very soft, almost the texture of cling wrap. - In the end, when the film was completely peeled, it ended up in a sticky ball due to a high concentration of plasticizer. 
During Testing	- The film could not be tested due to inadequate properties.

Quantitative → No quantitative data

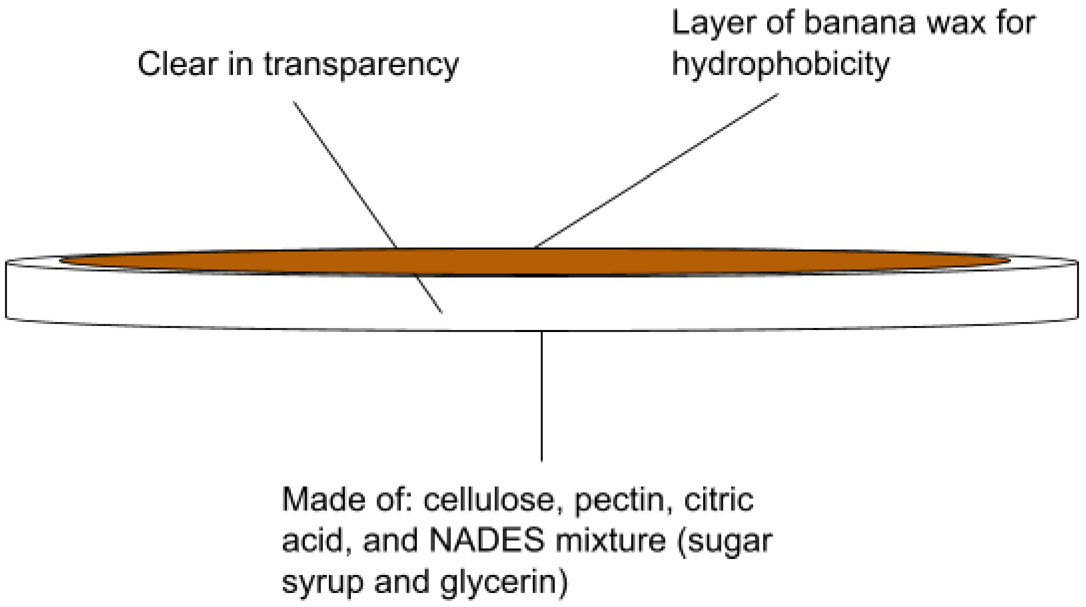
Future Improvements

This film was an improvement from the last. The only improvements:

1. Reduce plasticizer concentration.
2. Increase pectin concentration.

Phase 2-3

Design



The next film will be designed very meticulously. In previous films, the wet pectin mass was measured which ended up being very unreliable. This time, acidic conditions were measured and set to ensure the highest possible yield of pectin. Furthermore, the pectin will be dried completely before use to ensure proper calculations of the plasticizer. The table below showcases where each component of the film originated:

Film former: pectin ⟶ citrus peels
Reinforcement: cellulose ⟶ recycled paper
Reinforcement: wax ⟶ banana peels
Plasticizer: NADES ⟶ sugar syrup from pineapple peels and sodium acetate from acetic acid and sodium bicarbonate (1:1 molar ratio) *Note: vinegar and baking soda is not a form of waste.*
Crosslinking: calcium acetate → eggshells and acetic acid *Note: vinegar and baking soda is not a form of waste.*

Observations
Qualitative

While Making The Film	- Pectin was extracted twice. The pectin was obtained from orange peels as usual. However, this time, the pectin was

	extracted twice for increased yield. In the end, this provided plenty of pectin which is useful for getting a stronger, more peelable, film -   - This time, there was 2 grams of pectin. - The amount of plasticizer was calculated based on the mass of the pectin (30%) - This time, the solution was much more “slimy” which indicated adequate pectin concentrations. - The solution was also more thick, further indicating adequate pectin concentrations. - The pectin was very difficult to dissolve completely. - As a result, while pouring it was observed that much of the pectin settled at the bottom. When casting the film, more of the pectin solution was added to the middle of the film to prevent the film from failing completely due to inadequate pectin concentrations.
Day 1	- As the film was drying, it was noticed that the center was slightly thicker than other sides. - This is likely due to the pectin being added to the center later on.
Day 2	- The film was peelable, the first peelable film in this phase. - The center was, indeed, much thicker and clearer than the outsides

	- .    - The outside of the film also had many undissolved particles that caused some micro-holes. - Increased permeability - Banana wax was mainly only applied to the center as the outsides were uneven.
During Testing	- The micro-holes caused by the undissolved particles in the film caused increased permeability. This can be seen as both a positive and negative, Increased permeability increases oxygen exchange which is beneficial to soil microbes. But, it also causes lower water retention. - The undissolved particles also acted positively, providing some reinforcement which increased tear and puncture resistance. However, since the particles were undesired, they were uneven and unplanned, this is something to improve in future designs.

Quantitative

**For all categories in objective 1, the control is the Deionized (DI) water*

Objective 1 (Table 1) – Environmental Safety (Leachate Toxicity (Seed germination (%)))

Day	Film Type	Trial 1	Trial 2	Trial 3	Average
1	Conventional PE mulch film	0	0	0	**0**

	Conventional biodegradable mulch film	0	0	0	**0**
	Developed biodegradable film	0	0	0	**0**
	Control	0	0	0	**0**
2	Conventional PE mulch film	0	0	0	**0**
	Conventional biodegradable mulch film	0	0	0	**0**
	Developed biodegradable film	0	0	0	**0**
	Control	0	0	0	**0**
3	Conventional PE mulch film	0	0.05	0	**0.0167**
	Conventional biodegradable mulch film	0	0	0	**0**
	Developed biodegradable film	0	0	0	**0**
	Control	0	0	0	**0**
4	Conventional PE mulch film	0	0.05	0	**0.0167**
	Conventional biodegradable mulch film	0	0	0	**0**
	Developed biodegradable film	0	0	0.05	**0.0167**
	Control	0	0	0	**0**

5	Conventional PE mulch film	0	0.05	0	**0.0167**
	Conventional biodegradable mulch film	0	0	0	**0**
	Developed biodegradable film	0.05	0	0.05	**0.033**
	Control	0	0	0	**0**
6	Conventional PE mulch film	0.05	0.05	0	**0.033**
	Conventional biodegradable mulch film	0	0	0	**0**
	Developed biodegradable film	0.05	0.05	0.05	**0.05**
	Control	0	0	0	**0**
7	Conventional PE mulch film	0.05	0.05	0	**0.033**
	Conventional biodegradable mulch film	0	0	0	**0**
	Developed biodegradable film	0.05	0.05	0.05	**0.05**
	Control	0	0.05	0.1	**0.05**

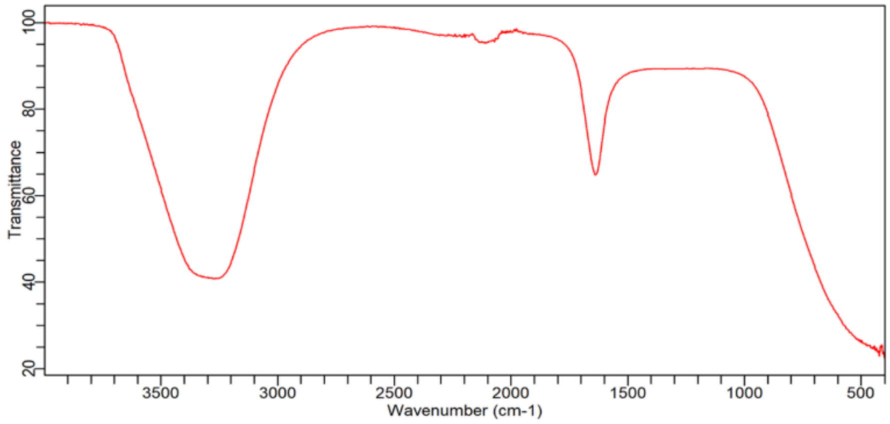
FTIR Analysis

FTIR analysis was done in order to potentially discover functional groups of concern in the films' leachates. However, the FTIR instrument was not able to pick up the functional groups due to two reasons:

1. The concentration of the leachates was too low.
2. The sample was aqueous. The water signals blocked much of the hydrocarbon signals.

As a result, all of the spectra ended up looking the same. Later on, even after letting the leachate sit for 20 days, nothing was seen.

All spectra were looking like this:



Objective 1 (Table 2) – Environmental Safety (Leachate Toxicity (Avg. Shoot Length after 7 days (cm)))

Film Type	Trial 1	Trial 2	Trial 3	Average
Conventional PE mulch film	0.025	0.015	0	0.020
Conventional biodegradable mulch film	0	0	0	0
Developed biodegradable film	0.03	0.025	0.03	0.028
Control	0	0.015	0.02	0.018

Physical Properties

	Thickness	Mass/Area	Density	Permeability (%)
Plastic 1	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Plastic 2	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Plastic 3	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0

Biodegradable 1	0.1 mm	0.0115 g/cm^2	1.23 g/cm^3	0
Biodegradable 2	0.1 mm	0.0115 g/cm^2	1.23 g/cm^3	0
Biodegradable 3	0.1 mm	0.0115 g/cm^2	1.23 g/cm^3	0
Pectin 1	0.1 mm	< 0.0141 g/cm^2	1.41 g/cm3	30
Pectin 2	0.2 mm	0.01667 g/cm2	0.83 g/cm3	30
Pectin 3	0.1 mm	< 0.0141 g/cm^2	1.41 g/cm3	30

	Thickness	Mass/Area	Density	Permeability
Plastic avg.	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Biodegradable avg.	0.1 mm	0.0115 g/cm^2	1.23 g.cm^3	0
Biodegradable +plastic avg.	0.1 mm	0.01080 g/cm^2 g/cm^2	1.08 g/cm^3	0
Pectin avg.	0.133 mm	0.01496 g/cm^2	1.21667 g/cm^3	30%
Minimum deviation	0.09	0.00972 g/cm^2	1.008 g/cm^3	0
Maximum deviation	0.11	0.01188 g/cm2	1.232 g/cm^3	0

Mechanical Properties

	Stiffness	Flexibility	Tear resistance	Puncture resistance
Plastic 1	3 cm	453.592 g	83 g	13 g
Plastic 2	3 cm	453.592 g	60 g	30 g
Plastic 3	2.5 cm	453.592 g	49 g	24 g
Biodegradable 1	2.5 cm	453.592 g	38 g	15 g
Biodegradable 2	3 cm	453.592 g	56 g	19 g

Biodegradable 3	2.5 cm	680.4 g	47 g	26 g
Pectin 1	2.5	226.8 g	23 g	50 g
Pectin 2	2.5	453.59 g	60 g	48 g
Pectin 3	3	226.8 g	49 g	80 g

	Stiffness	Flexibility	Tear resistance	Puncture resistance
Plastic avg.	2.83 cm	453.592 g	64 g	22.33 g
Biodegradable avg.	2.67 cm	529.2 g	47 g	20 g
Biodegradable +plastic avg.	2.75 cm	491.396 g	55.5 g	21.165 g
Pectin avg.	2.67 cm	302.4 g	44 g	59.33 g
Minimum deviation	2.48 cm	442.26 g	49.95 g	19.0485 g
Maximum deviation	3.03 cm	540.54 g	61.05 g	23.2815 g

Section 4: Phase 3: Prototype Refinement (Final Prototype)

Reason for Starting Phase 3

Phase 2 of this project aimed to develop a biodegradable film made out of waste sources such as orange peels, paper waste, pineapple peels, banana peels, and eggshells. Using these waste materials, the objective was to create a more cost-effective film as previous prototypes lacked financial scalability.

However, while trying to extract biopolymers myself, I realised that it was very difficult to attain pure pectin from at-home processes.This was especially over-ambitious as this project is already niche and novel. Taking the direction of extracting biopolymers from waste sources made this project extremely complex. Extracting biopolymers from waste sources, specifically, can become a completely different project.

That is why, this phase of this project goes back to the first phase and focuses on developing an effective prototype using biopolymers from industrial facilities. This prioritises creating an effective film without harming its functionality.

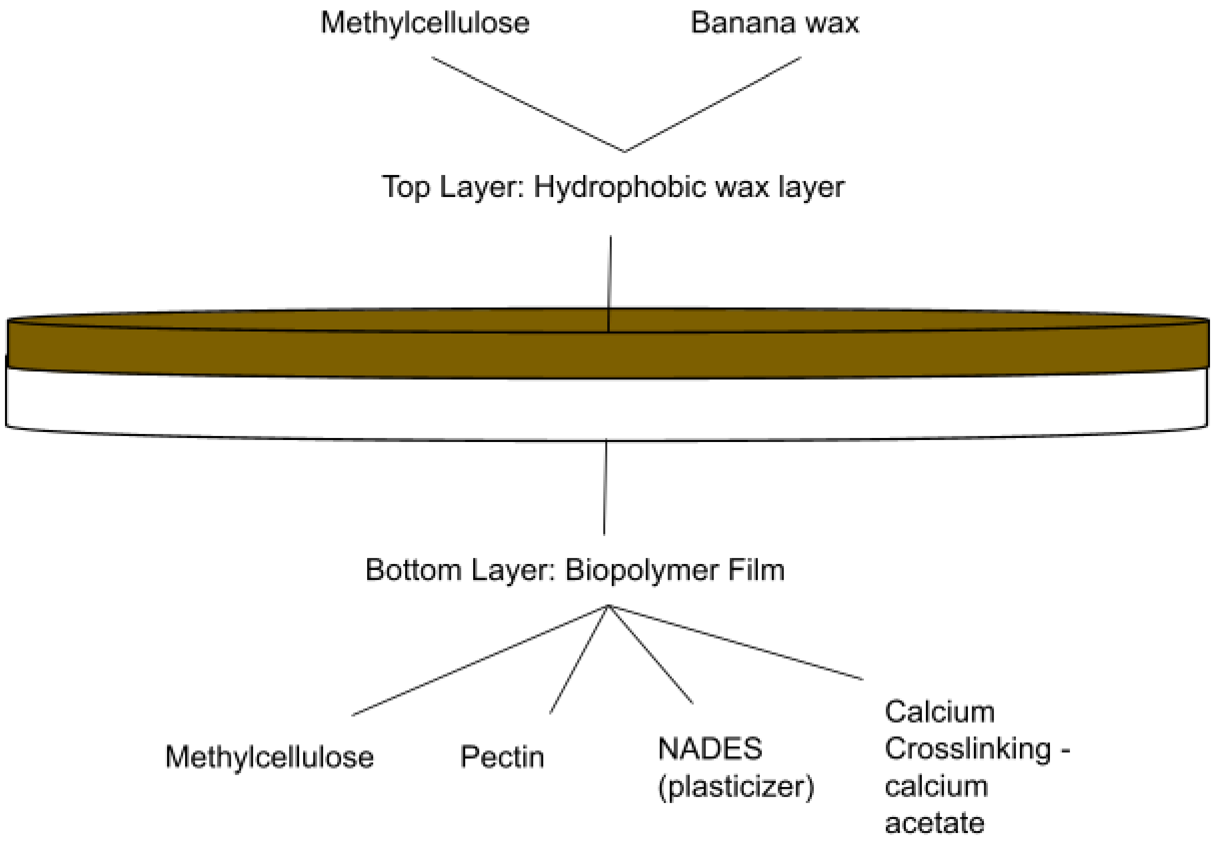
However, this exploratory work was not completely pointless. There were many things learned from this phase that can be of-use. For example, the incorporation of NADES. Eutectic mixtures are significantly more viscous which makes its leaching much slower. Furthermore, with NADES, there are many papers that showcase that you need a smaller amount to have the same effect.

Furthermore, this phase of this project also taught me skills of resilience and persistence as there were countless failures upon failures.

In summary, this project aims to return to the original objective which was focusing on leachate toxicity instead of trying to derive biopolymers from waste sources which was exploratory and diverging from the original purpose of this project.

Phase 3-1

Design



Previously, a hydrophobic layer was made by rubbing the banana peel wax onto the surface of the film. However, this was ineffective in creating a uniform coating on top. As a result, there were some areas which were more hydrophobic than the others.

To make it easier to coat the film uniformly a paper using banana leaf wax (which is made of the same materials as banana peel wax) to make a hydrophobic coating was used to form the method for the coating:

1. Extract banana peel wax, or a wax-rich extract (can’t be fully pure at home).
2. Gather materials: 100 mL water, 1.5 tsp banana wax, ½ tsp methylcellulose.
3. Dissolve methylcellulose in water after letting it hydrate.
4. Add ½ tsp of banana wax at a time and spread it out evenly while the solution is still heated
    a. The solution should be heated the rest of the time.
5. Dip the film into the waxy mixture after everything is evenly spread out.
6. Instantly take the film out of the solution.
7. Leave the solution out on a surface to dry (mickey mouse coasters in this case).
8. After drying, it should have a waxy layer on top.

Observations

Qualtivative

While Making The Film	- Pectin concentration was adequate, as seen with the texture of the solution (gel-like and slimy). - The solution felt more viscous as time went on. - The methylcellulose only dissolved at room temperature. - The process was similar to phase 2.
Day 1	- The film was drying efficiently. No major problems were observed.
Day 2	- The film was dried and peeled. - It was soaked in calcium acetate for crosslinking. - The film was left to dry on the coasters. - One observation made is that when the film does not dry flat, it becomes very “crinkled.” In other words, this means that the film easily takes shape of what it is contained in while drying.

Day 3	- The films were dry and ready for the wax coating.
	- While making the wax coating:
	  - The banana wax had a really low yield and so this limited how much could be used.
	  - The banana wax only stayed liquid at high temperatures but methyl cellulose did not dissolve properly at high temperatures due to its unique gelling abilities. This created problems as the cellulose was insoluble at high temperatures and the wax did not apply properly at lower temperatures. This made the application extremely uneven and the film did not work.

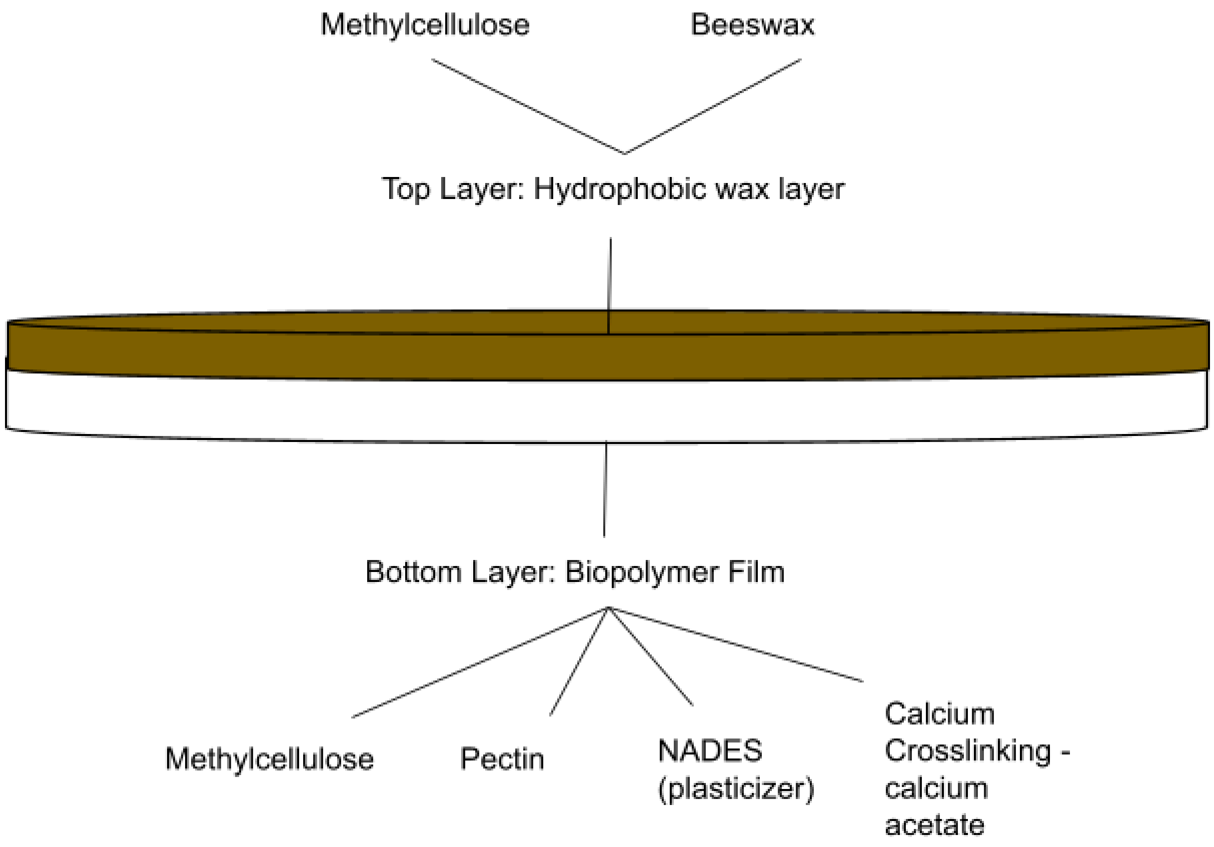
Areas to Improve:

1. Wax coating
    a. The chosen polymer was not suitable for the application due to methylcelluloses' unique gelling capacity. Hence, a new biopolymer (crosslinked pectin) will be chosen.
    b. Secondly, the yield of banana wax was very low. Beeswax is easier to access and has historically, and currently, been used as water-proofing agents.

Other than the improvement of the wax coating, the films' performance was comparable to previous prototypes in phase 1.

Phase 3-2

Design



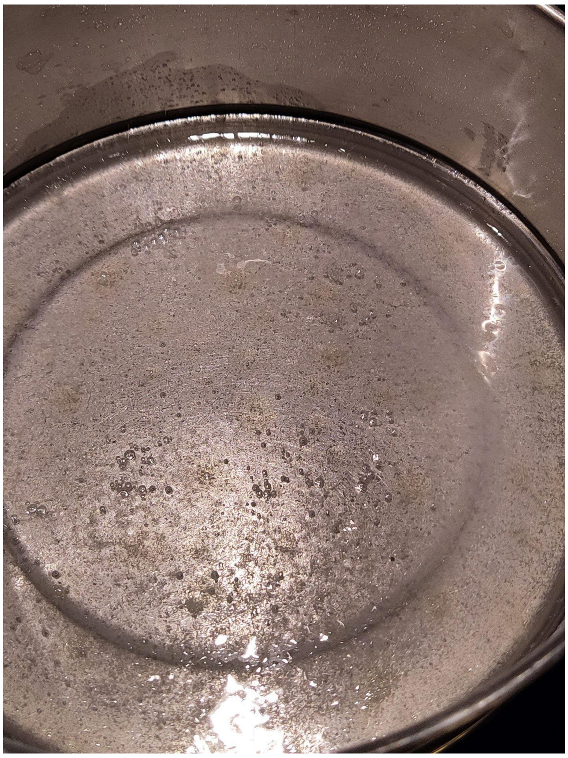
In the previous film, the wax coating did not work effectively due to the unique gelling abilities of methyl cellulose which was incompatible with wax. Furthermore, due to the low yield of banana wax, beeswax will be used instead as it is easier to access.

The same method will be used to make the wax coating but the banana wax will be swapped out for beeswax. The methylcellulose will be swapped with pectin. After the coating is made it will be crosslinked with calcium acetate.

Observations

Qualitative

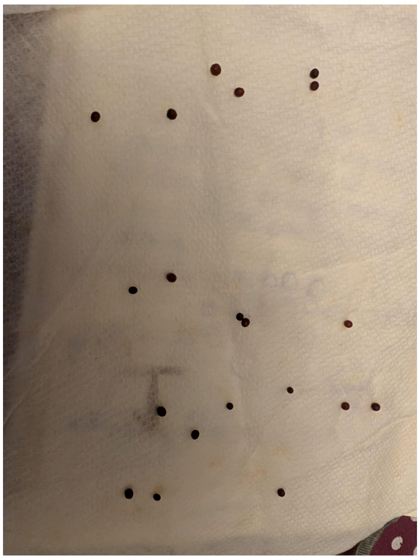
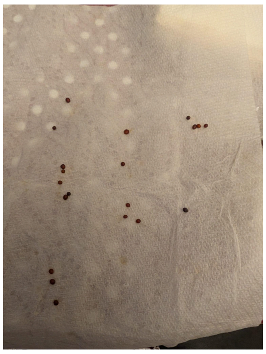
While Making The Film	- The film performance was extremely similar to the previous film, being made of the same ingredients.
	    - Pectin concentration was adequate, as seen with the texture of the solution (gel-like and slimy).
	    - The solution felt more viscous as time went on.
	    - The methylcellulose only dissolved at room temperature.
	    - The process was similar to phase 2.
	- A major change was actually the dissolving of the methylcellulose. I added the pectin first and then dissolved the methylcellulose after it sat in the fridge for about an hour.

Day 1	- The film was drying efficiently. No major problems were observed, just as in the previous trial.
Day 2	- The film was dried and peeled. - It was soaked in calcium acetate for crosslinking. - The film was left to dry on the coasters. - Again, the process was similar to the previous trial.
Day 3	- The films were dry and ready for the wax coating. - While making the wax coating: - The pectin was dissolved then the banana wax was added. Instead of being completely uniform there were some sections that had “blobs” of wax.  - When the film was soaked, it felt “bumpy” and not completely uneven. So, I tried to conserve the film by wiping off the coating. What ended up happening was that only the extra pectin particles were removed and there was still a waxy layer on the film. - In the end, the coating worked after the excess was removed.

During Testing	- Mechanical/Physical Properties:
	  - The film, as expected, performed similarly to phase 1. However, it was slightly thinner. I am not sure what caused this as I used the same concentration of all biopolymers.
	- Bioassay
	  - Originally, radish seeds were used but they germinated in one day which means they are likely more resistant to environmental changes than mustard seeds.
	  - In the mustard seed bioassay, there was similar toxicity performance as previous sections which is logical a the same ingredients were used.

	-      

Quantitative

Environmental Toxicity - Bioassay

Objective 1 (Table 1) – Environmental Safety (Leachate Toxicity (Seed germination (/20)))

Day	Film Type	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
1	Conventional PE mulch film	0	0	0	0	0
	Conventional biodegradable mulch film	0	0	0	0	0
	Developed biodegradable film	0	0	0	0	0
	Control	0	0	0	0	0
4	Conventional PE mulch film	0	0	0	0	1
	Conventional biodegradable mulch film	0	0	0	0	0
	Developed biodegradable film	0	0	0	0	1
	Control	1	0	0	0	0
7	Conventional PE mulch film	0	0	0	1	1
	Conventional biodegradable mulch film	0	0	1	0	1
	Developed biodegradable film	1	1	0	2	1
	Control	1	0	1	1	1

Objective 1 (Table 2) – Environmental Safety (Leachate Toxicity (Seed germination (%)))

Day	Film Type	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
1	Conventional PE mulch film	0	0	0	0	0	**0**
	Conventional biodegradable mulch film	0	0	0	0	0	**0**
	Developed biodegradable film	0	0	0	0	0	**0**
	Control	0	0	0	0	0	**0**
4	Conventional PE mulch film	0	0	0	0	5	**1**
	Conventional biodegradable mulch film	0	0	0	0	0	**0**
	Developed biodegradable film	0	0	0	0	5	**1**
	Control	5	0	0	0	0	**1**
7	Conventional PE mulch film	0	0	0	5	5	**2**
	Conventional biodegradable mulch film	0	0	5	0	5	**2**
	Developed biodegradable film	5	5	0	10	5	**5**
	Control	5	0	5	5	5	**4**

Objective 1 (Table 3) – Environmental Safety (Leachate Toxicity (Avg. Root Length after 7 days (cm)))

Film Type	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average

Conventional PE mulch film	0	0	0	0.5	0.3	0.16
Conventional biodegradable mulch film	0	0	2.5	0	0.3	0.56
Developed biodegradable film	1.3	3.5	0	0.25	0.1	1.03
Control	0.1	0	2	1.5	2	1

Physical Properties

	Thickness	Mass/Area	Density	Permeability (%)
Plastic 1	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Plastic 2	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Plastic 3	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Biodegradable 1	0.1 mm	0.0115 g/cm²	1.23 g/cm^3	0
Biodegradable 2	0.1 mm	0.0115 g/cm²	1.23 g/cm^3	0
Biodegradable 3	0.1 mm	0.0115 g/cm²	1.23 g/cm^3	0
Pectin 1	0.1 mm	< 0.0141 g/cm²	1.141 g/cm3	0
Pectin 2	0.1 mm	0.0177 g/cm2	1.77 g/cm3	10
Pectin 3	0.1 mm	< 0.0141 g/cm²	1.141 g/cm3	0

	Thickness	Mass/Area	Density	Permeability
Plastic avg.	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Biodegradable avg.	0.1 mm	0.0115 g/cm²	1.23 g.cm^3	0
Biodegradable	0.1 mm	0.01080 g/cm²	1.08 g/cm³	0

+plastic avg.		g/cm^2		
Pectin avg.	0.133 mm	0.01496 g/cm²	1.35 g/cm^3	3.3%
Minimum deviation	0.09	0.00972 g/cm^2	1.008 g/cm³	0
Maximum deviation	0.11	0.01188 g/cm2	1.232 g/cm³	0

Mechanical Properties

	Stiffness	Flexibility	Tear resistance	Puncture resistance
Plastic 1	3 cm	453.592 g	83 g	13 g
Plastic 2	3 cm	453.592 g	60 g	30 g
Plastic 3	2.5 cm	453.592 g	49 g	24 g
Biodegradable 1	2.5 cm	453.592 g	38 g	15 g
Biodegradable 2	3 cm	453.592 g	56 g	19 g
Biodegradable 3	2.5 cm	680.4 g	47 g	26 g
Pectin 1	3	680.4 g	45 g	60 g
Pectin 2	2.5	453.59 g	57 g	73 g
Pectin 3	3	680.4 g	50 g	43 g

	Stiffness	Flexibility	Tear resistance	Puncture resistance
Plastic avg.	2.83 cm	453.592 g	64 g	22.33 g
Biodegradable avg.	2.67 cm	529.2 g	47 g	20 g
Biodegradable +plastic avg.	2.75 cm	491.396 g	55.5 g	21.165 g
Pectin avg.	2.83 cm	604.8 g	51 g	56.67 g

Minimum deviation	2.48 cm	442.26 g	49.95 g	19.0485 g
Maximum deviation	3.03 cm	540.54 g	61.05 g	23.2815 g

Discussion

This project aimed at creating a biodegradable mulch film, aiming to address current concerns of biodegradable films' leachate toxicity and their impact on agricultural soil health and plant yield. To create a prototype that is effective, this project was broken down into two objectives:

1. Creating a biodegradable mulch film with lower leachate toxicity than conventional biodegradable and plastic mulch films
2. Ensuring the mulch film is as effective as possible, with a maximum compromise of ±10% in physical and mechanical properties compared to conventional biodegradable and plastic mulch films.

Summary of Project

Phase 1: Initial Prototype Development (Baseline Prototype)

- Developed first mulch film using pectin, methylcellulose, and wax
- Established baseline mechanical strength and flexibility
- Identified initial feasibility → found that cost may be a limiting factor

Phase 2: Exploratory Prototype Development (Waste-derived materials)

- Tested film formulations with biopolymers extracted at home from waste sources
- Observed inconsistency and reduced performance
- Determined that excessive exploratory modification negatively impacted performance

Phase 3: Prototype Refinement (Final Prototype)

- Returned to the baseline formulation
- Improved properties through final refinements

Phase 1

Section 1: Material Selection/Film Design

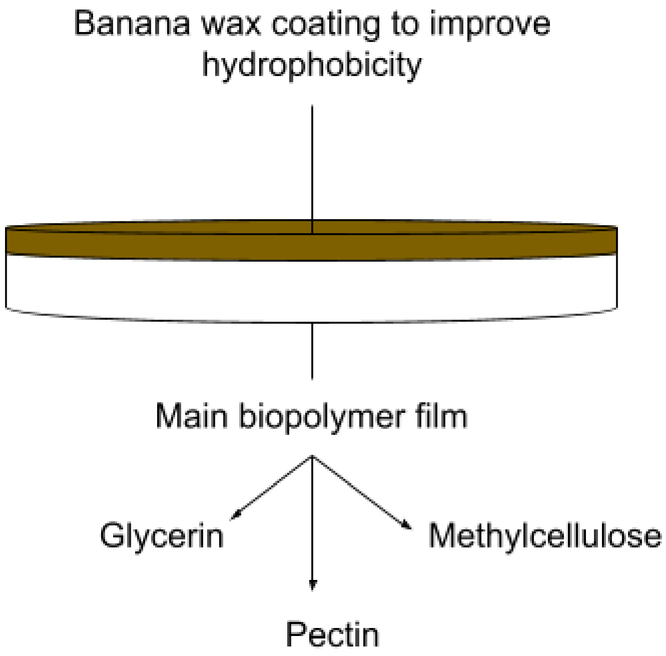
The developed biodegradable film design focused on optimising the balance between leachate toxicity and effectiveness as defined in the objectives. As a result, the final design had a bi-layer approach. Essentially, the main film was made of a biodegradable polymer: pectin, as well as a glycerin as a plasticiser. The film also had mild crosslinking through calcium acetate to improve strength. Finally, the film had a wax coating from banana wax. This bi-layer approach allowed for improved properties. The bottom layer was made of pectin, which acted like a hydrocolloid, trapping water. The top, hydrophobic layer, prevents rapid degradation of the film and ensures it stays preserved for the whole growing cycle.

Choosing natural biopolymers instead of petroleum derived polymers was intentional. Petroleum derived polymers have the potential to introduce microplastics and other additives in the soil. Certain hydrocarbons from petroleum-derived polymers may cause problems to plants including oxidative stress.

Adding a hydrophobic layer on top also has another benefit → slower leaching. Since pectin and methylcellulose are water soluble, it is quick to degrade in soil. Though these materials are not inherently bad for soil, when introduced too quickly it may cause problems due to high concentrations (high concentrations of any substance may become problematic). With slow release of leachates, there are less chances of reducing soil health/crop yield.

Material	Use
Pectin (Pamona’s pectin)	Pectin is the main film used in the final prototype.
Methylcellulose	Methylcellulose is also a film former which compensates for the weaknesses of pectin such as high solubility.
Glycerin	Acting as a plasticizer, increasing the flexibility of the film. The plasticizer slips into the polymer matrix, reducing intermolecular forces and increasing chain mobility.
Calcium acetate	Caused ionic crosslinking which improved the mechanical properties of the film through increased strength.

Banana peel wax	Increases hydrophobicity which slows the rate of leaching additives like soil.



The final film, as stated, above has two layers: a top layer for improved hydrophobicity and a main biopolymer film made of biopolymers.

Section 2: Lower Leachate Toxicity

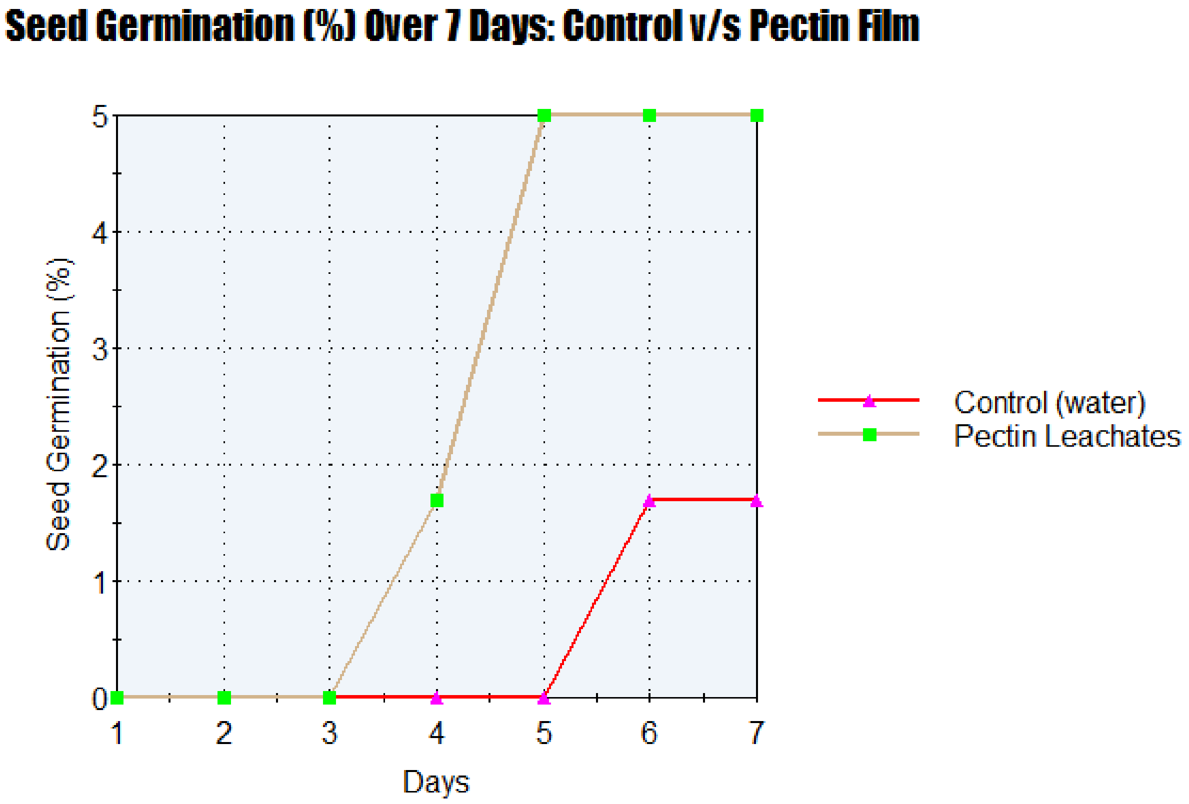
Lower leachate toxicity was the first objective of this project. This was explored in this project due to a lack of availability of a mulch film that tackles this issue.

Leachate toxicity was measured by a bioassay analysis in this section. The bioassay done was on seed germination (%) and shoot length. When assessing the environmental toxicity of leachates, texting on seeds is effective as seeds are more sensitive to environmental changes in this phase, meaning there is added vulnerability during this phase.

Seed Germination (%)

Days	1	2	3	4	5	6	7
Avg. % of sprouted seeds (control)	0	0	0	0	0	1.7	1.7

Avg. % of sprouted seeds (pectin leachate)	0	0	0	1.7	5	5	5


Seed Germination (%) Over 7 Days: Control v/s Pectin Film

Seed germination in the group of seeds exposed to the pectin film was much faster. At the end of the testing period, the average percentage of sprouted seeds in the pectin leachate group was 5%, while in the control group, it was only 1.7%. This means the pectin film actually allowed for increased germination, with about 194% more germination. This is a significant amount, showcasing how the film is likely less toxic than conventional biodegradable counterparts.

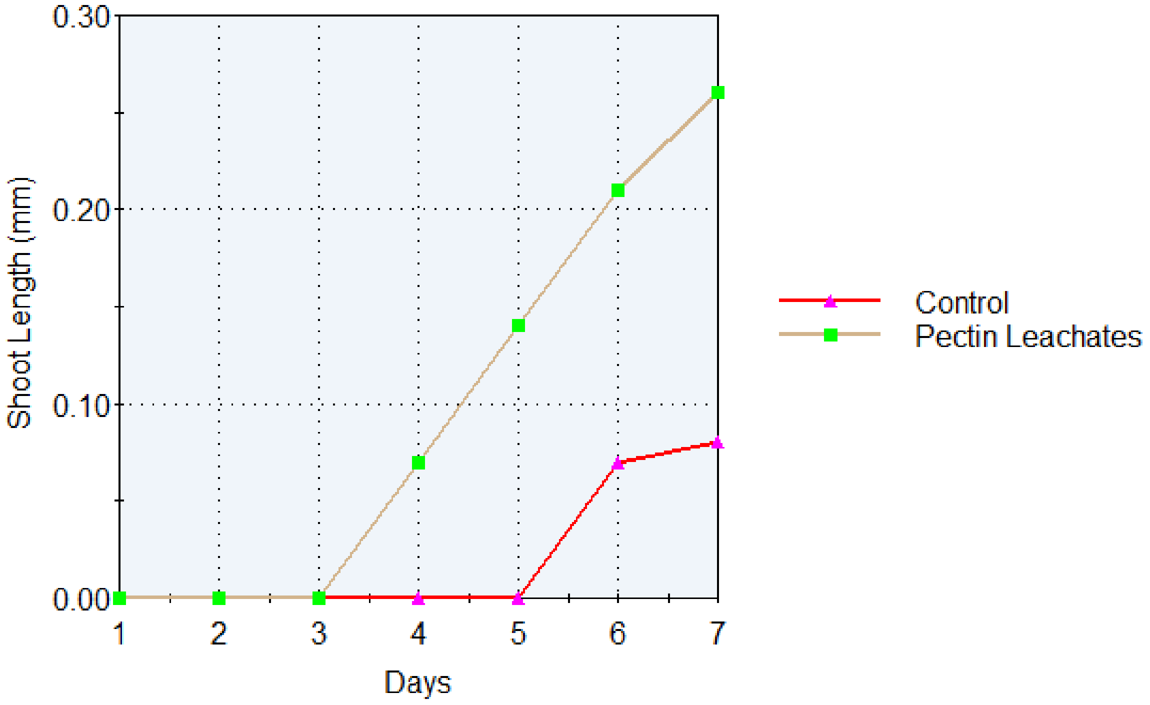
The reasoning for this is that pectin is a polysaccharide found in many plants. As it degrades, pectin releases sugars into the soil which act as essential sources of fuel for microorganisms which, in the end, improve soil properties.

However, the control group did not have this added benefit which is why less germination was seen here.

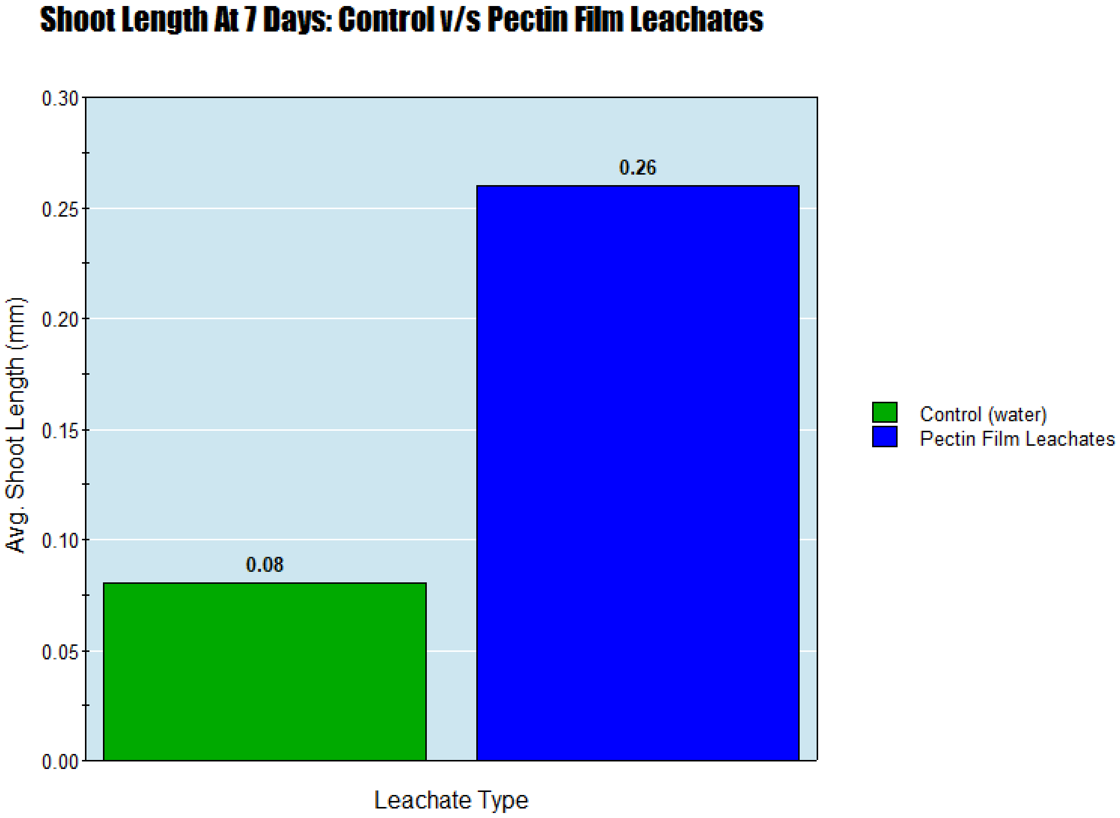
Shoot Length

Days	1	2	3	4	5	6	7
Avg. length of control seeds	0 mm	0 mm	0 mm	0 mm	0 mm	0.07 mm	0.08 mm
Avg. length of leachate seeds	0 mm	0 mm	0 mm	0.07 mm	0.14 mm	0.21 mm	0.26 mm

Shoot Length Over 7 Days: Control v/s Pectin Film Leachates



Over 7 days, it is clear there was faster growth in the groups exposed to the pectin films' leachates. Precisely, there was roughly 0.0114 mm of shoot growth per day. In the control group. In contrast, there was roughly 0.0371 mm of shoot growth per day in the pectin leachate group. There was roughly 225% more growth per day in the group exposed to pectin leachates.



At the end of the 7 days, on average, the seeds exposed to the pectin films' leachates had a higher shoot length. Precisely, the control group had an average of 0.08 mm shoot length and the pectin leachate exposed group had an average of 0.26 mm. There was roughly 225% more growth by the end of the 7 days in the group exposed to pectin leachates.

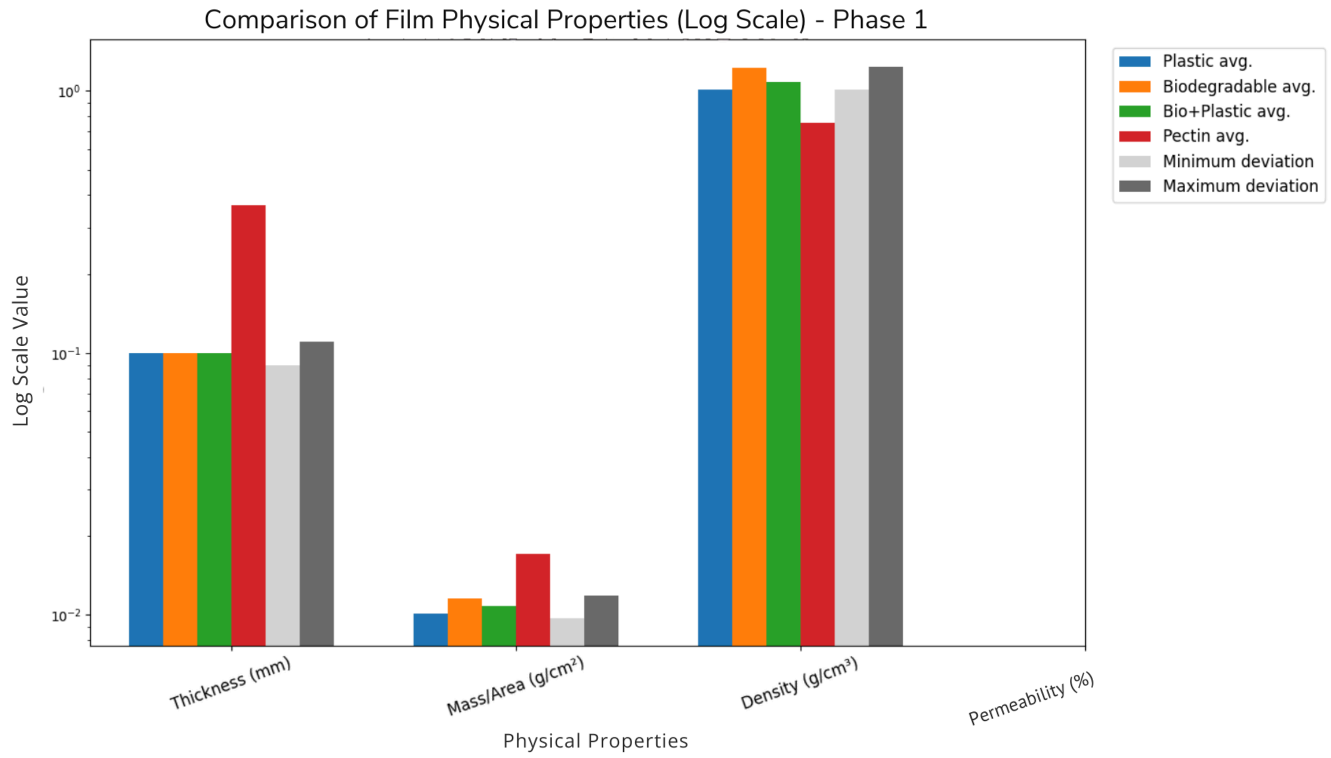
In summary, the group of seeds exposed to film leachates germinated faster and grew faster. This strongly indicates that the developed film has low toxicity, and possibly even a potential for improving crop yield through its leachates.

Section 3: Similar Effectiveness

Physical Properties

	Thickness	Mass/Area	Density	Permeability
Plastic avg.	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Biodegradable avg.	0.1 mm	0.0115 g/cm^2	1.23 g.cm^3	0
Biodegradable +plastic avg.	0.1 mm	0.01080 g/cm^2 g/cm^2	1.08 g/cm^3	0
Pectin avg.	0.367 mm	0.0171 g/cm^2	0.7531 g/cm^3	0

Minimum deviation	0.09	0.00972 g/cm^2	1.008 g/cm³	0
Maximum deviation	0.11	0.01188 g/cm2	1.232 g/cm³	0



Thickness

Thickness was originally important to measure as it provides insight on a variety of performance aspects. Firstly, the films' thickness determines its stiffness. If a film is more stiff, it is more resistant to bending. Stiffness may be problematic if the film has to be applied to agricultural soils. If the film is too stiff, it will be difficult to wrap it on top of the soil.

However, on the flip side, high thickness may also be beneficial. Thickness allows a film to be more durable as it becomes more resistant to a variety of forces. Though this is a benefit, it has its limitations, if the thickness is not balanced to ensure low stiffness, it can lead to an ineffective film.

The determined minimum thickness the film had to meet was 0.09 mm and the maximum thickness was 0.11 mm. The developed film exceeded this and had a thickness of 0.367 mm. The developed film was roughly 230% thicker than the target thickness.

This is a significant difference, and if the stiffness is not effectively balanced, this could be a major tradeoff.

An explanation for this is that using at-home methods such as solution casting has lower precision and creates an irregular film. In industrial applications, proper machinery would make it much more feasible to make a thinner film.

Mass/area

Mass/area was evaluated as this provided insight on the material usage for a given area. If this number is too high it can lead to lower economic feasibility due to requirements for lots of material which can increase the cost of the film.

This also connects to thickness. If the mass/area is high, it indicates high material usage for a specific area which increases thickness. Again, the same aspects apply. It is important to measure this factor as it provides insights on stiffness and durability of the film.

The developed film also exceeded the determined goal which was a range of 0.00972 g/cm^2-0.01188 g/cm^2 the film had a mass/area of 0.0171 g/cm^2. This is roughly 44% above the target.

This is not as significant of a difference in comparison to thickness. If thickness is reduced, this number will also fall within the target range.

This likely happened because using at-home methods such as solution casting has lower precision and creates an irregular film. It is much more difficult to make a thin film without proper machinery.

Density

Density was evaluated as it gives insights on the material performance as well. Firstly it provides insight on how tightly packed the molecules are within a substance. Secondly, it is an indicator of porosity. If the density is low, it can indicate holes which may compromise permeability. Finally, density indicates dissolved oxygen or air pockets left in the film. This can alter its mechanical strength.

The determined minimum density the film had to meet was 1.008 g/cm^3 and the maximum density was 1.232 g/cm^3. The developed film did not meet this, falling short of the minimum target, and had a density of 0.7531 g/cm^3. The film was 25% less than the required density.

This is not a significant difference. I predict the density was low due to air pockets. While dissolving the pectin, it is very difficult to agitate the solution without dissolving excess oxygen. So, in the end, this caused lower density in the developed film.

Permeability

Permeability is one of the most important factors in determining the performance of the film. However, similarly to thickness, this aspect may also have its pros and cons.

With low permeability, the film traps water vapour which decreases evaporation. Through decreased evaporation, there is increased moisture retention which not only supports the growth of plants but also helps to reduce water consumption for agriculture.

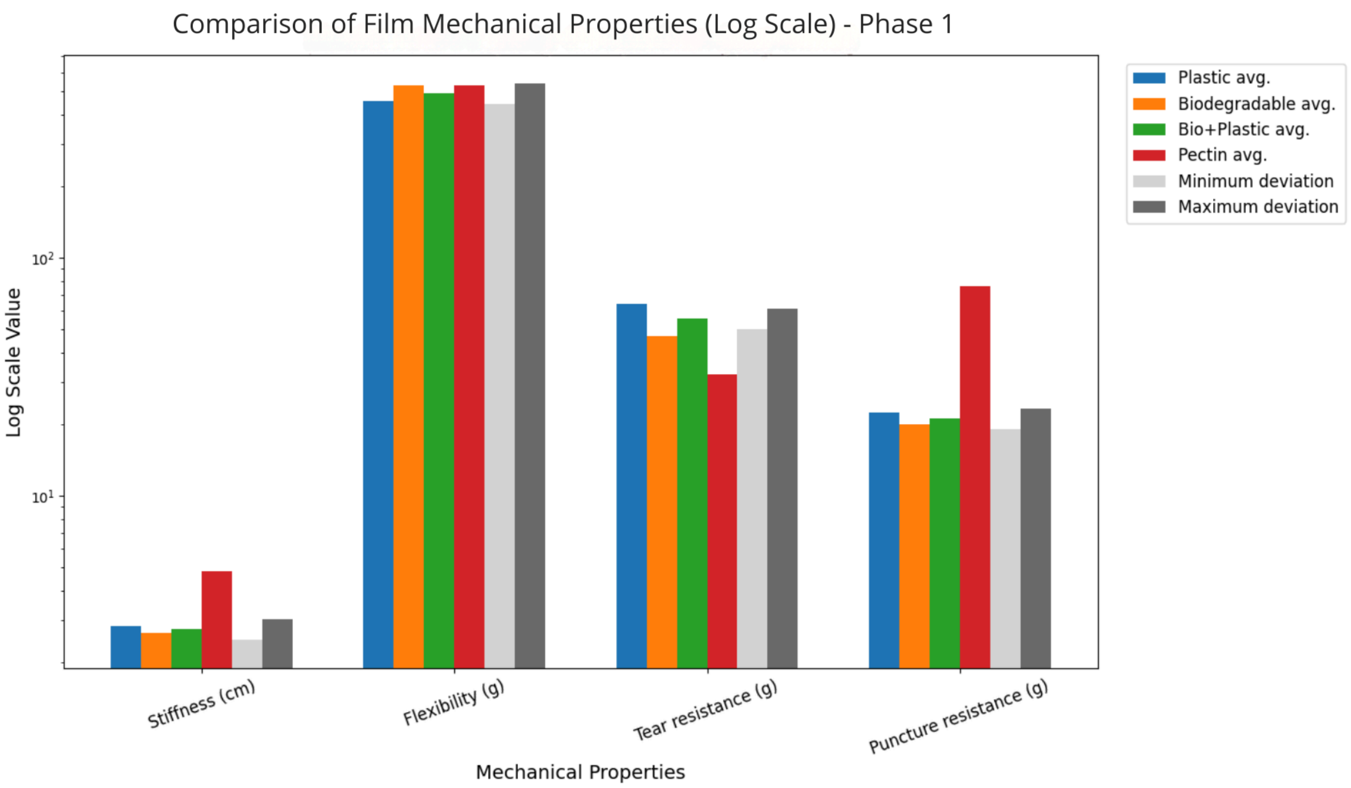
Despite these benefits, there can be a lot of harm if permeability is low. This is because of anaerobic bacteria. Certain anaerobic bacteria can turn nitrogen present in soil into polluting compounds such as nitrous oxide. If there is not enough gas (oxygen specifically) exchange, it can harm soil microbes and plants will not get nitrogen in the forms they need to grow. Hence, with a permeable film, it still allows for exchange of gases which can benefit soil aeration.

The film itself did not have any permeability, at least in the given time frame. However, it is known that pectin is able to act as a hydrocolloid, swelling when it comes into contact with water. As a result, the pectin traps water which supports water retention.

The target permeability was 0%, which was the amount for both biodegradable and plastic films. The developed pectin film met this range.

Mechanical Properties

	Stiffness	Flexibility	Tear resistance	Puncture resistance
Plastic avg.	2.83 cm	453.592 g	64 g	22.33 g
Biodegradable avg.	2.67 cm	529.2 g	47 g	20 g
Biodegradable +plastic avg.	2.75 cm	491.396 g	55.5 g	21.165 g
Pectin avg.	4.83 cm	530.7 g	32.33 g	76 g
Minimum deviation	2.48 cm	442.26 g	49.95 g	19.0485 g
Maximum deviation	3.03 cm	540.54 g	61.05 g	23.2815 g



Stiffness

Stiffness was measured as it is essential to the design. Mulch films need to be able to, with ease, wrap around the soil in agricultural soil. If the film is too stiff, this ability is compromised. As determined in the previous section, the film was found to be immensely thick, far surpassing the target range. It was recognized that this would likely increase stiffness and it did.

Stiffness was measured by assessing the overhand length of the film at 45 degrees. The determined target range for stiffness was between 2.48 cm-3.03 cm. The overhang length of the developed film to bend 45 degrees was 4.83 cm. This is roughly 59% more than the maximum target stiffness value.

This may become problematic in real-life applications as high stiffness can cause difficulties in applying the film on agriculture soils. This high stiffness is certainly caused by the high thickness.

The reason for high thickness, as mentioned above, is due to lack of access to precise technology to achieve a thin and even film. In the future, this aspect of the project should be improved.

Flexibility

Flexibility is one of the most important factors in determining the functionality of an agricultural mulch film. The film should easily wrap around the soil for maximum effectiveness. If a mulch is not flexible enough, it compromises many of the benefits of a mulch film. For example, if the soil is not covered well, it does not trap water vapours and the film loses its benefit of improving soil moisture and water retention.

Furthermore, if a film does not cover the soil well, there may be pockets of exposed soil. In these areas, weeds are able to grow and the films' ability to prevent weeds is also compromised.

Flexibility was measured by assessing the amount of force required to break the film. The determined target range for flexibility was between 442.26 g-540.54 g. The actual flexibility was 530.7 g. This met the target range.

Glycerin served as a good plasticizer in improving film flexibility. In the end, the final film was flexible enough.

Tear Resistance

Tear resistance showcases how a film is able to resist a tear from continuing after being started. Tear resistance needs to be balanced. On one hand, low tear resistance can impair durability. However, if tear resistance is too high, it will be difficult for farmers to adjust the film size for certain conditions.

Tear resistance was measured by evaluating the amount of weight required to continue a tear. The determined target range for tear resistance was between 49.95 g-61.05 g. The actual tear resistance was 32.33 g. This was roughly 35% lower than the minimum target tear resistance.

A possible reason for low tear resistance is because pectin is a weak biopolymer on its own. In the future it may be beneficial to add certain additives or raise the amount of methylcellulose to combat this issue.

Puncture Resistance

Puncture resistance shows how easily the film is susceptible to punctures, or holes. This is important to assess as mulch films are especially susceptible to holes on irregular or rough soils.

Tear resistance was measured by evaluating the amount of weight required to create a puncture. The determined target range for puncture resistance was between 19 g-23 g. The actual tear resistance was 76 g. This was 230.4% higher than the maximum target puncture resistance, meaning the film exceeded this factor.

The reason for this is likely thickness. It has been made clear in previous sections that thickness was too high. However, this still has benefits such as increased puncture resistance. Puncture resistance is harder to achieve when the film is too thin.

Section 4: Summary

In summary, the main tradeoff of the developed film was thickness which caused certain sections of the film performance to be compromised. There is also strong evidence with the bioassay that the developed film has low leachate toxicity, have over 2x more shoot length by the end of the 7 days and roughly 194% more germination.

Phase 2

Section 1: Material Selection/Film Design

The developed biodegradable film design focuses on optimising the balance between leachate toxicity and effectiveness. As a result, the final design had a bi-layer approach. Essentially, the main film would be made of a biodegradable polymer, pectin, as well as a NADES as a plasticiser. The film will also have mild crosslinking through calcium acetate to improve strength. Finally, the film had a wax coating. This bi-layer approach allowed for improved properties.

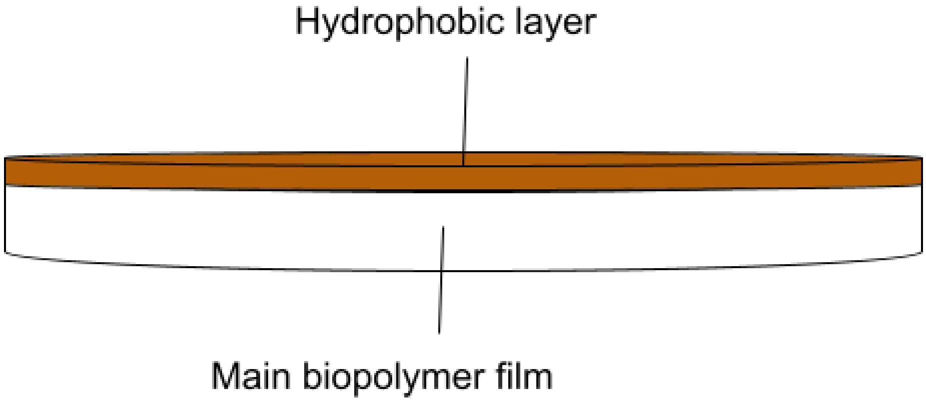
The table below shows the materials selected for the final prototype as well as its source.

Material	Source	Use
Pectin	Orange Peels	Pectin is the main film used in the final prototype.
Microcellulose-like suspension	Paper waste	Fibre reinforcement which increases the strength of the film.

NADES	Glycerin and pineapple peel extracts	Acting as a plasticizer, increasing the flexibility of the film. The plasticizer slips into the polymer matrix, reducing intermolecular forces and increasing chain mobility.
Calcium acetate	Eggshells and acetic acid	Caused ionic crosslinking which improved the mechanical properties of the film through increased strength.
Banana peel wax	Banana peels	Increases hydrophobicity which slows the rate of leaching additives like soil.

Unlike traditional biodegradable mulch films, this prototype specifically included natural materials that would cause very minimal harm to plants and soil health. Hence, it is a more sustainable option for agriculture. For example, the plasticiser chosen was a NADES; these substances are known to serve as a more environmentally friendly alternative to traditional plasticisers. Furthermore, this film has a hydrophobic layer made of banana peel wax. As a result, the speed at which substances are leached is slowed without compromising biodegradability or increasing antioxidant properties through using more hydrophobic biopolymers such as chitin.

In the end, the combination of these two reasons allowed for an effective film that was comparable to conventional biodegradable and plastic mulch films.

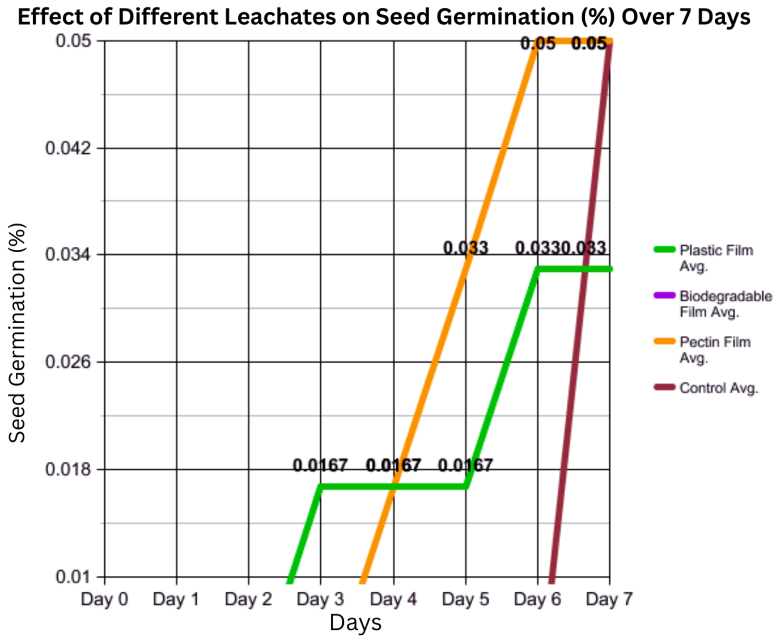


Section 2: Lower Leachate Toxicity

The leachate toxicity were analysed as to increase the amount of in two ways for phase 2 of this project. Firstly, a bioassay was done to evaluate how the films' leachates directly impact plants. This was done by assessing the impacts of the films' leachates on germination rate and shoot length

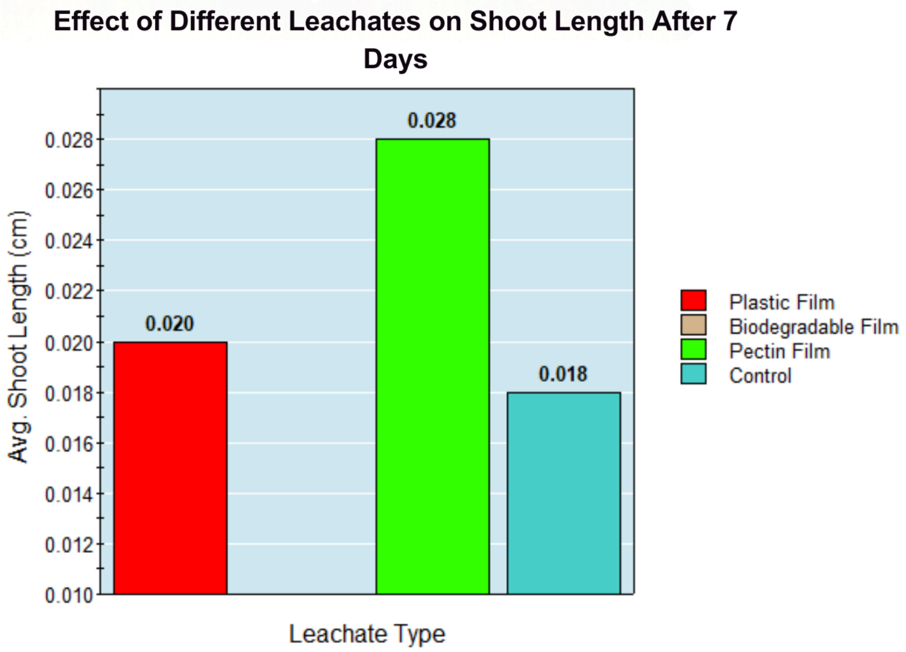
Germination.

Days	1	2	3	4	5	6	7
Avg. % of sprouted seeds (control)	0	0	0	0	0	0	0
Avg. % of sprouted seeds (pectin leachate)	0	0	0	0.0167	0.033	0.05	0.05
Avg. % of sprouted seeds (plastic film leachate)	0	0	0.0167	0.0167	0.0167	0.033	0.033
Avg. % of sprouted seeds (con. biodegradable leachate)	0	0	0	0	0	0	0.05



Shoot Length at 7 days

Film Type	Average
Conventional PE mulch film	0.020
Conventional biodegradable mulch film	0
Developed biodegradable film	0.028
Control	0.018



Seeds exposed to the plastic films' leachates were the first to germinate. However, the control had a large spike of growth in the end. So, overall the control and the plastic leachates allowed for comparable impacts on the germination rates. This is re-emphasized on shoot length data. The control average was only 10% lower than the plastic average.

The reason for faster germination in the plastic film despite the potential of microplastics is likely because plastic is not soluble in water. This means even after days of soaking the plastic film, it is difficult to get a high enough concentration of plastic in the leachate solution to impact seed germination significantly..

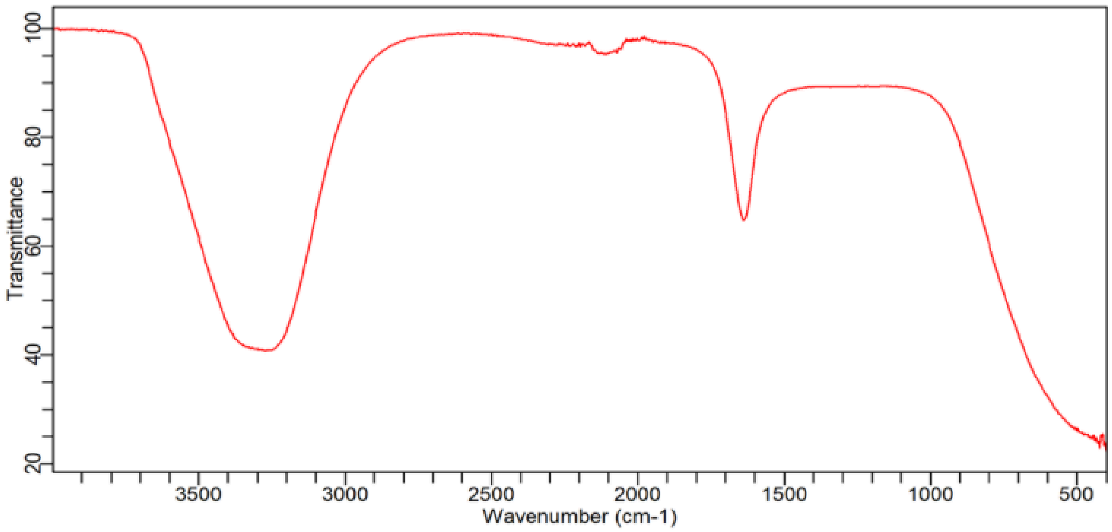
The possible reasoning behind why the pectin film had much higher levels of seed germination is possibly through nutrients introduced through the organic material used. Pectin is a natural polysaccharide derived from plant cell walls and may have provided nutrients such as sugars that may have supported microbes, and in the end, the seed.

The biodegradable film did not have any growth. The reason for this is because PBAT/PLA films were already, in previous literature, found to have higher potential of leachate toxicity. Additionally, the biodegradable film used in this experiment was sourced from compost bags rather than actual biodegradable films. Compost bags often contain additives such as plasticizers, stabilizers, or processing agents, which may not be suitable to seeds during germination stages.

FTIR

Furthermore, FTIR analysis was also done. However some/the results were not significant.

Many of the spectra looked the same and any significant signals were blocked by water.

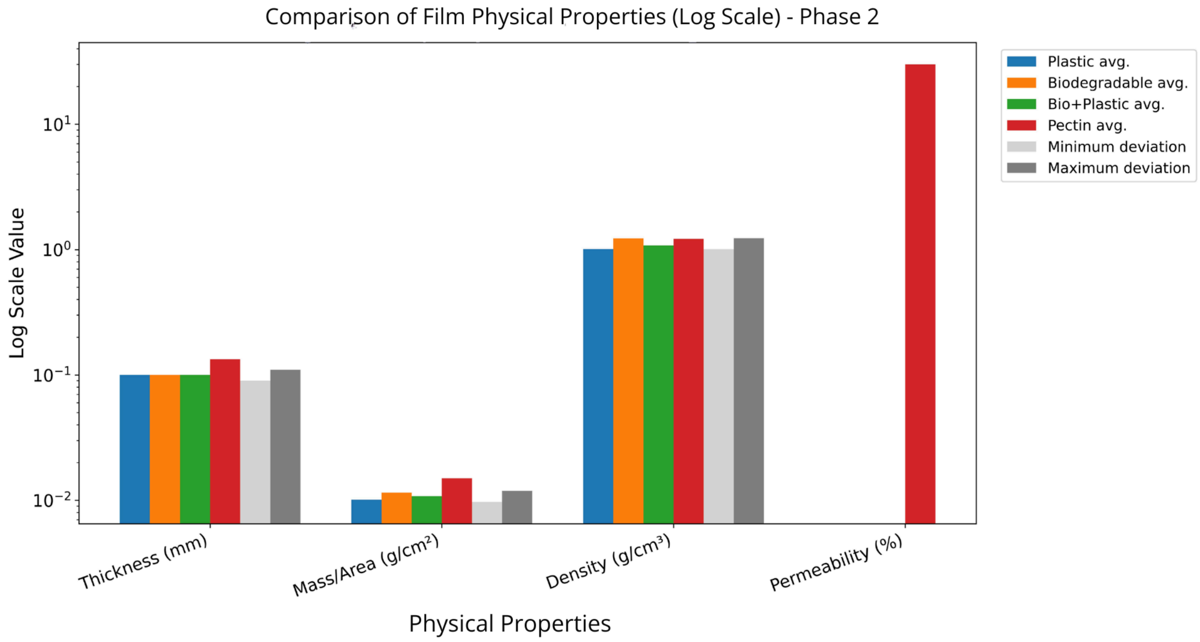


Section 3: Similar Effectiveness

**See tables in methods section for raw data*

Physical Properties

	Thickness	Mass/Area	Density	Permeability
Plastic avg.	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Biodegradable avg.	0.1 mm	0.0115 g/cm^2	1.23 g.cm^3	0
Biodegradable +plastic avg.	0.1 mm	0.01080 g/cm^2 g/cm^2	1.08 g/cm^3	0
Pectin avg.	0.133 mm	0.01496 g/cm^2	1.21667 g/cm^3	30
Minimum deviation	0.09	0.00972 g/cm^2	1.008 g/cm^3	0
Maximum deviation	0.11	0.01188 g/cm2	1.232 g/cm^3	0



Thickness

Thickness was originally important to measure as it provides insight on a variety of performance aspects. Firstly, the films' thickness determines its stiffness. If a film is more stiff, it is more resistant to bending. Stiffness may be problematic if the film has to be applied to agricultural soils. If the film is too stiff, it will be difficult to wrap it on top of the soil.

However, on the flip side, high thickness may also be beneficial. Thickness allows a film to be more durable as it becomes more resistant to a variety of forces. Though this is a benefit, it has its limitations, if the thickness is not balanced to ensure low stiffness, it can lead to an ineffective film.

The determined minimum thickness the film had to meet was 0.09 mm and the maximum thickness was 0.11 mm. The developed film exceeded this and had a thickness of 0.133 mm. The developed film was roughly 21% thicker than the target thickness.

This is much lower than the original thickness which suggests improvements in this aspect through lower pectin concentration due to difficulties in attaining the expected pectin yield.

However, as you will see later in this phase, the lower pectin concentration negatively impacted the film performance in mechanical properties.

Mass/area

Mass/area was evaluated as this provided insight on the material usage for a given area. If this number is too high it can lead to lower economic feasibility due to requirements for lots of material which can increase the cost of the film.

This also connects to thickness. If the mass/area is high, it indicates high material usage for a specific area which increases thickness. Again, the same aspects apply. It is important to measure this factor as it provides insights on stiffness and durability of the film.

The developed film also exceeded the determined goal which was a range of 0.00972 g/cm^2-0.01188 g/cm^2. The film had a mass/area of 0.01496 g/cm². This is roughly 26% above the target.

Though, again, this is much closer to the target, there were still some problems as there was less pectin use. There were lower pectin concentrations due to difficulties in attaining the expected pectin yield.

However, the lower pectin concentration negatively impacted the film performance in mechanical properties.

Density

Density was evaluated as it gives insights on the material performance as well. Firstly it provides insight on how tightly packed the molecules are within a substance. Secondly, it is an indicator of porosity. If the density is low, it can indicate holes which may compromise permeability. Finally, density indicates dissolved oxygen or air pockets left in the film. This can alter its mechanical strength.

The determined minimum density the film had to meet was 1.008 g/cm³ and the maximum density was 1.232 g/cm³. The developed film did meet this, and had a density of 1.21667 g/cm^3.

This likely happened because there was a lower amount of air bubbles increasing the volume due to more meticulous and careful solution preparation.

Permeability

Permeability is one of the most important factors in determining the performance of the film. However, similarly to thickness, this aspect may also have its pros and cons.
With low permeability, the film traps water vapour which decreases evaporation. Through decreased evaporation, there is increased moisture retention which not only supports the growth of plants but also helps to reduce water consumption for agriculture.

Despite these benefits, there can be a lot of harm if permeability is low. This is because of anaerobic bacteria. Certain anaerobic bacteria can turn nitrogen present in soil into polluting compounds such as nitrous oxide. If there is not enough gas (oxygen specifically) exchange, it can harm soil microbes and plants will not get nitrogen in the forms they need to grow. Hence, with a permeable film, it still allows for exchange of gases which can benefit soil aeration.

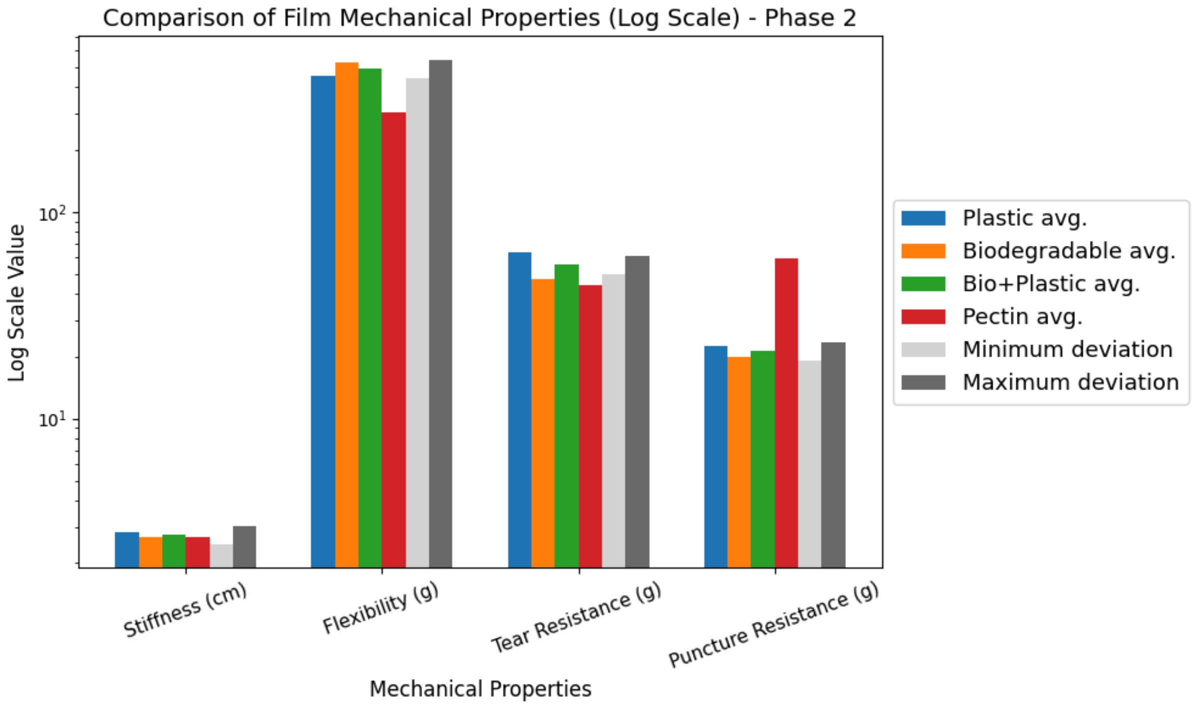
It is known that pectin is able to act as a hydrocolloid, swelling when it comes into contact with water. As a result, the pectin traps water which supports water retention.

The target permeability was 0%, however, the pectin film had a permeability of 30% which may even be beneficial. However, the developed film in this phase had undissolved particles which created small holes on the film. This is why water was able to permeate.

As seen later in this phase, the holes and undissolved particles actually ended up compromising the film mechanical properties.

Mechanical Properties

	Stiffness	Flexibility	Tear resistance	Puncture resistance
Plastic avg.	2.83 cm	453.592 g	64 g	22.33 g
Biodegradable avg.	2.67 cm	529.2 g	47 g	20 g
Biodegradable +plastic avg.	2.75 cm	491.396 g	55.5 g	21.165 g
Pectin avg.	2.67 cm	302.4 g	44 g	59.33 g
Minimum deviation	2.48 cm	442.26 g	49.95 g	19.0485 g
Maximum deviation	3.03 cm	540.54 g	61.05 g	23.2815 g



Stiffness

Stiffness was measured as it is essential to the design. Mulch films need to be able to, with ease, wrap around the soil in agricultural soil. If the film is too stiff, this ability is compromised. As determined in the previous section, the film was found to be immensely thick, far surpassing the target range. It was recognized that this would likely increase stiffness and it did.

Stiffness was measured by assessing the overhand length of the film at 45 degrees. The determined target range for stiffness was between 2.48 cm-3.03 cm. The stiffness of the film was 2.67 cm. This was in the required range.

The film is less stiff now that it had a lower thickness than the previous film.

Flexibility

Flexibility is one of the most important factors in determining the functionality of an agricultural mulch film. The film should easily wrap around the soil for maximum effectiveness. If a mulch is not flexible enough, it compromises many of the benefits of a mulch film. For example, if the soil is not covered well, it does not trap water vapours and the film loses its benefit of improving soil moisture and water retention.

Furthermore, if a film does not cover the soil well, there may be pockets of exposed soil. In these areas, weeds are able to grow and the films' ability to prevent weeds is also compromised.

In this film, the flexibility did not meet the minimum target which was between 442.26 g-540.54 g. The film had an average flexibility of roughly 302.4 g which was 31.6% lower than the minimum deviation.

Limited flexibility, as mentioned above, significantly reduces the effectiveness of the film and makes it more susceptible to damage and lower effectiveness. The reason for the lowered flexibility in this film is likely because of the pectin extraction method creating undissolved solids in the film.

Pectin was extracted at home using orange peels. However, even with acid hydrolysis, some orange peel particles remained and the pectin was not as pure as pomona's pectin. Hence, there were many orange particles in the film. These particles acted similarly to the coconut coir in prototype 2. They ended up creating microholes that made the film more prone to tearing.

In the future, using lab methods to extract pectin can prove to be extremely effective to not only repurpose waste (as the main objective of this section), but also create an effective film.

Tear Resistance

Tear resistance showcases how a film is able to resist a tear from continuing after being started. Tear resistance needs to be balanced. On one hand, low tear resistance can impair durability. However, if tear resistance is too high, it will be difficult for farmers to adjust the film size for certain conditions.

Tear resistance was measured by evaluating the amount of weight required to continue a tear. The determined target range for tear resistance was between 49.95 g-61.05 g. The actual tear resistance was 44 g. This was roughly 12% lower than the minimum target tear resistance.

The reason behind this is the same as flexibility. The orange peel particles cause small holes in the film which made it much more prone to tears.

In some cases reinforcements with fibres from food waste sources may be useful in increasing tear resistance, however since this aspect was uncontrolled as the orange peel particles were undesired, it created a film with less effectiveness.

Puncture Resistance

Puncture resistance shows how easily the film is susceptible to punctures, or holes. This is important to assess as mulch films are especially susceptible to holes on irregular or rough soils.

Tear resistance was measured by evaluating the amount of weight required to create a puncture. The determined target range for puncture resistance was between 19 g-23 g. The actual tear resistance was 59.33 g. This was 230.4% higher than the maximum target puncture resistance, meaning the film exceeded this factor.

The reason for this is likely a mixture of thickness and the undissolved orange particles.The film still had a slightly higher thickness than the plastic and conventional biodegradable film. This allowed for more puncture resistance.

Furthermore, the slight reinforcement caused by the orange particles may have also benefited puncture resistance. It is important to realise, however, that since this puncture resistance was not uniform, it creates many more problems than benefits so it is important to have controlled reinforcements with orange particles.

Section 4: Summary

In the end, it was realised that trying to extract the biopolymers from waste sources at home was an extremely difficult task. To attain pure pectin proper lab spaces are very beneficial.

Due to difficulties extraction of 100% pure pectin, there were some leftover orange particles that significantly compromised mechanical properties compared to the previous film.

Trying to extract biopolymers from waste sources was, in reality, a diversion from the main objective. Developing a film with low leachate toxicity is already an under-researched area and trying to go more niche and extract the biopolymers from waste sources was very ambitious for this project. Exploration towards this area should be done in the future, when there is more access to resources such as lab or industrial facilities. For now, this project will continue to be developed using pure pectin.

Phase 3

Section 1: Material Selection/Film Design

The developed biodegradable film design focuses on optimising the balance between leachate toxicity and effectiveness. As a result, the final design had a bi-layer approach. Essentially, the main film would be made of a biodegradable polymer, pectin, as well as a NADES as a plasticiser. Which is similar to the previous phase.

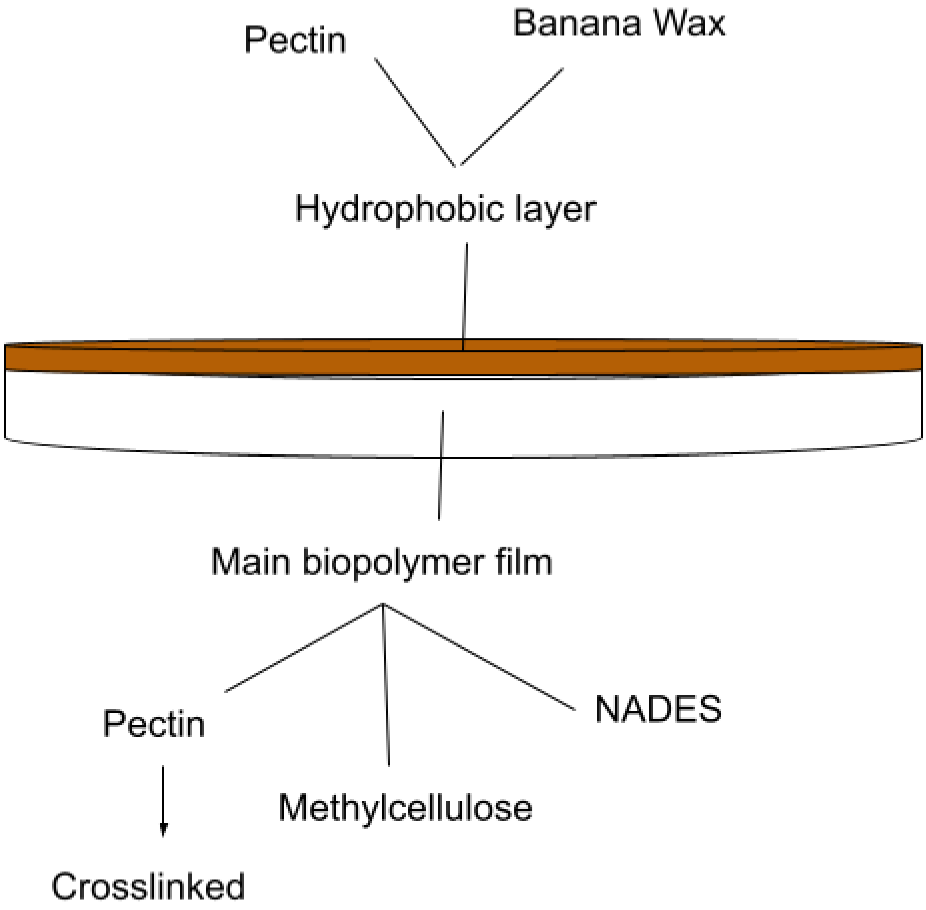
After trying to achieve good results from a waste-derived film, it was realised that this objective was overambitious and slightly diverting away from the main objective. This is why, in the end, store-bought pectin was used instead. This was much simpler to work with and significantly reduced the amount of time required to make the film.

The table below summarises the chosen materials and their purpose.

Material	Use
Pectin	Pectin was one of the film-forming biopolymers in combination with methylcellulose. Pectin was used as it increases flexibility due to its gel-like structure. It is found between the cell wall and the cell which is why it must be so flexible.
Methylcellulose	Methylcellulose was the other film-forming biopolymer. Cellulose is the rigid structure that makes up the cell wall. Due to its rigidity, this biopolymer balances pectin and adds more strength.
The final ratio of methylcellulose:pectin was 1:1. This created a balance of both biopolymer properties.	
NADES	Acting as a plasticizer, increasing the flexibility of the film. The plasticizer slips into the polymer matrix, reducing intermolecular forces and increasing chain mobility. NADES were used in the phase as well. This is because the film made with NADES showed better physical and mechanical properties. Using a NADES also ensures more stability in heat. Lastly, NADES exhibit reduced plasticizer migration which is critical for the environment.
Calcium acetate	Caused ionic crosslinking which improved the mechanical properties of the film through increased strength.
Banana peel wax	Increases hydrophobicity which slows the rate of leaching additives like soil.

Unlike traditional biodegradable mulch films, this prototype specifically included natural materials that would cause very minimal harm to plants and soil health. Hence, it is a more sustainable option for agriculture. For example, the plasticiser chosen was a NADES; these substances are known to serve as a more environmentally friendly alternative to traditional plasticisers. Furthermore, this film has a hydrophobic layer made of banana peel wax. As a result, the speed at which substances are leached is slowed without compromising biodegradability or increasing antioxidant properties through using more hydrophobic biopolymers such as chitin.

In the end, the combination of these two reasons allowed for an effective film that was comparable to conventional biodegradable and plastic mulch films.

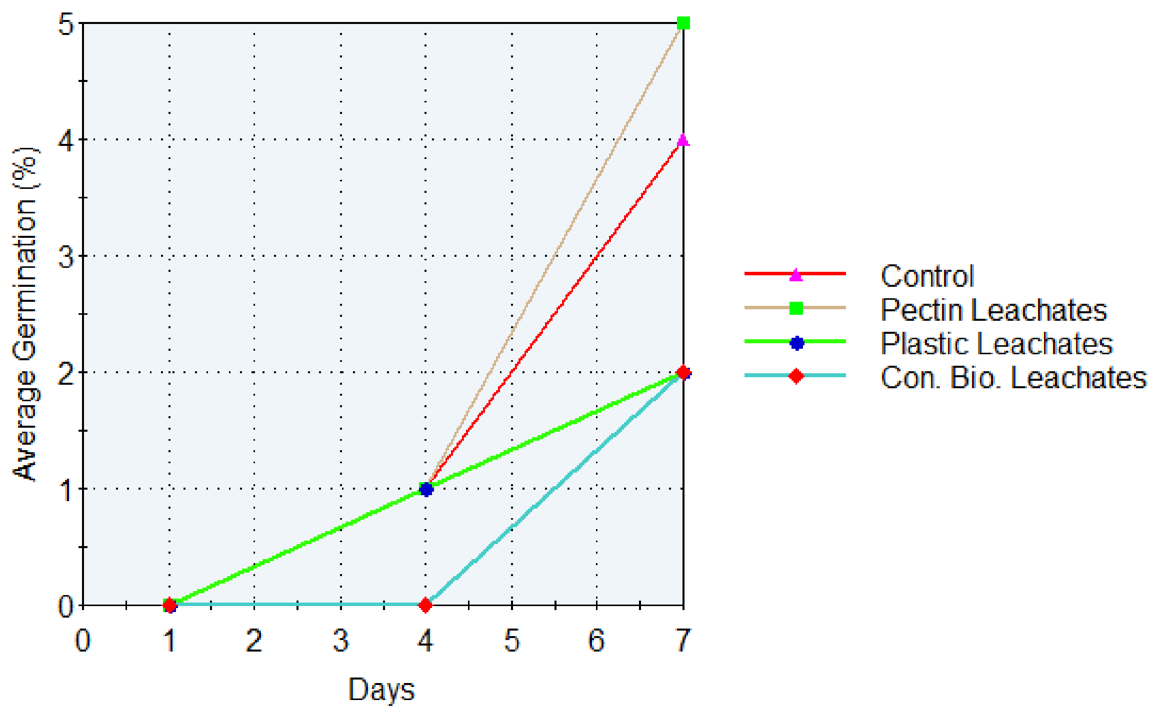


Section 2: Lower Leachate Toxicity

The leachate toxicity was measured in a seed germination bioassay. Mustard seeds were exposed to different film leachates as well as a control group given just water. There were five trials for each leachate. In the end, it was found that the film exposed to the leachates of the developed film not only was less toxic but also had increased seed germination. This is seen in the data below.

Days	1	4	7
Avg. % of sprouted seeds (control)	0	1	4
Avg. % of sprouted seeds (pectin leachate)	0	1	5
Avg. % of sprouted seeds (plastic film leachate)	0	1	2
Avg. % of sprouted seeds (con. biodegradable leachate)	0	0	2

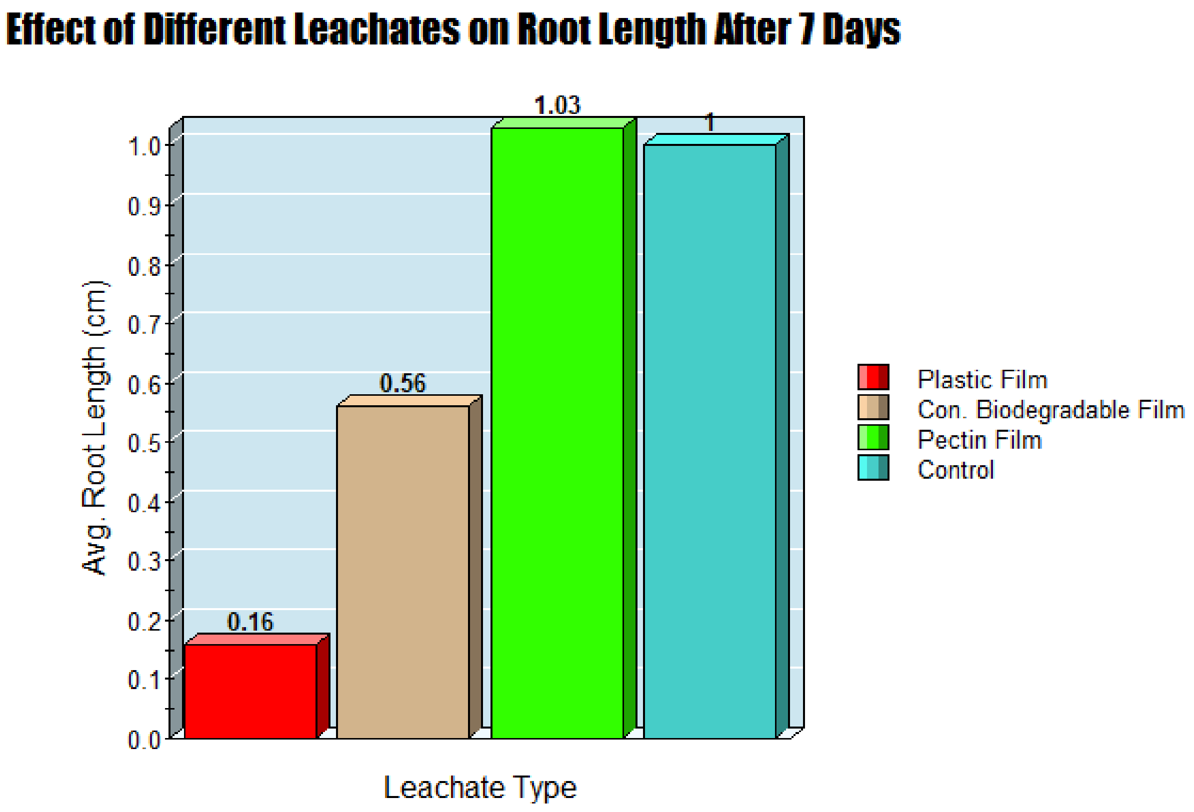
Average Seed Germination (%) Over 7 Days



Average Root Length After 7 Days (cm)

Film Type	Average
Conventional PE mulch film	0.16

Conventional biodegradable mulch film	0.56
Developed biodegradable film	1.03
Control	1



Effect of Different Leachates on Root Length After 7 Days

A bioassay is a test done on living organisms themselves. The films’ leachates were tested directly on mustard seeds which allows for data directly applicable to plants. The reason for testing on seed germination is sensitivity. During germination, seeds are more vulnerable to environmental changes. So, it is suitable to test on the plants during this time.

Seeds exposed to the conventional biodegradable film leachates were the last to germinate. By day 4, all groups had at least one germinated seed except for the biodegradable film. The reason for this can be that the conventional biodegradable film was more toxic due to the fact it is not meant specifically for plants. The film used in this test was obtained from compostable bags which may have certain additives that are not meant for plants.

Seeds exposed to the plastic film leachates grew slower than the control group. In the end, it had the least amount of growth as seed in the graph showcasing root length after 7 days. With an average of only 0.16 cm, it had a roughly 145% lower germination than the control group and a roughly 146% lower germination than the pectin film.

Seeds exposed to the conventional biodegradable film had roughly 111% more germination than the plastic film. This is contradicting results in the previous experiment where the biodegradable film had no germination. This may be explained by an outlier in the test which had an average of 188% longer root length than the rest of the trials.

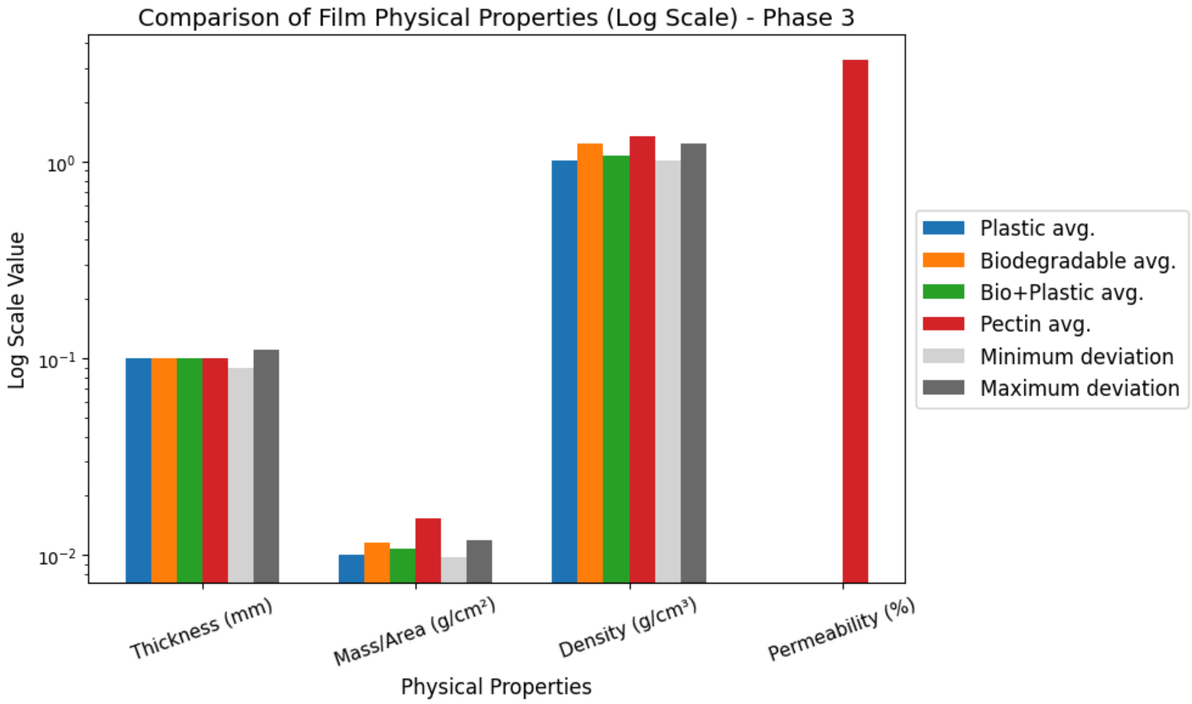
Finally, the pectin film had the most germination. The pectin film had a higher shoot length than all leachate types. The seeds exposed to the pectin film leachates had an average of 146% more root length compared to the plastic film and 59% more root length compared to the seeds exposed to the conventional biodegradable film leachates. Furthermore, the pectin film also had the highest germination rate with an average of roughly 22% more germination than the control group.

In the end, the pectin film not only exhibited lower toxicity but also encouraged seed germination. The reason for this may be that the pectin film introduced polysaccharides and minerals which supported microbes and seed germination. These results significantly support the conclusion that the developed film exhibits lower leachate toxicity compared to conventional biodegradable and plastic mulch films.

Section 3: Similar Effectiveness

Physical Properties

	Thickness	Mass/Area	Density	Permeability
Plastic avg.	0.1 mm	0.010101 g/cm^2	1.01 g/cm^3	0
Biodegradable avg.	0.1 mm	0.0115 g/cm²	1.23 g.cm^3	0
Biodegradable +plastic avg.	0.1 mm	0.01080 g/cm² g/cm^2	1.08 g/cm³	0
Pectin avg.	0.1 mm	0.0153 g/cm²	1.35 g/cm^3	3.3%
Minimum deviation	0.09	0.00972 g/cm^2	1.008 g/cm³	0
Maximum deviation	0.11	0.01188 g/cm2	1.232 g/cm³	0



Thickness

In initial tests, it was observed that thickness was the hardest to control. The reason for this was limited access to lab-grade or industrial tools to control thickness. If thickness is not balanced it can lead to compromised strength if too low and increased stiffness if too high.

The determined minimum thickness the film had to meet was 0.09 mm and the maximum thickness was 0.11 mm. The developed film exceeded this and had a thickness of 0.1 mm. The developed film met the requirement for thickness.

A potential reason for this is a more balanced pectin and methylcellulose concentration which prevents excess thickness.

Mass/area

Mass/area was evaluated as this provided insight on the material usage for a given area. If this number is too high it can lead to lower economic feasibility due to requirements for lots of material which can increase the cost of the film.

This also connects to thickness. If the mass/area is high, it indicates high material usage for a specific area which increases thickness. Again, If the thickness is not balanced it can lead to compromised strength if too low and increased stiffness if too high

The developed film also exceeded the determined goal which was a range of 0.00972 g/cm^2-0.01188 g/cm^2. The film had a mass/area of 0.0153 g/cm². This is roughly 25% above the target.

Though the target was exceeded, the reason for this may not be that the film genuinely has higher mass per area. Instead, it may be because the scale I was using was not precise enough to measure such a low mass. So the mass was estimated to be “<1g.” This is undefined which makes it difficult to accurately measure mass/area.

Density

Density was evaluated as it gives insights on the material performance as well. Firstly it provides insight on how tightly packed the molecules are within a substance. Secondly, it is an indicator of porosity. If the density is low, it can indicate holes which may compromise permeability. Finally, density indicates dissolved oxygen or air pockets left in the film. This can alter its mechanical strength.

The determined minimum density the film had to meet was 1.008 g/cm^3 and the maximum density was 1.232 g/cm^3. The developed film did not meet this, having a density of 1.35 g/cm^3. This exceeded the maximum deviation by 9%.

Again, though the target was exceeded, the reason for this may not be that the film genuinely has a higher density. Instead, it may be because the scale I was using was not precise enough to measure such a low mass. So the mass was estimated to be “<1g.” This is undefined which makes it difficult to accurately measure mass/area.

Permeability

Permeability is one of the most important factors in determining the performance of the film. However, similarly to thickness, this aspect may also have its pros and cons.
With low permeability, the film traps water vapour which decreases evaporation. Through decreased evaporation, there is increased moisture retention which not only supports the growth of plants but also helps to reduce water consumption for agriculture.

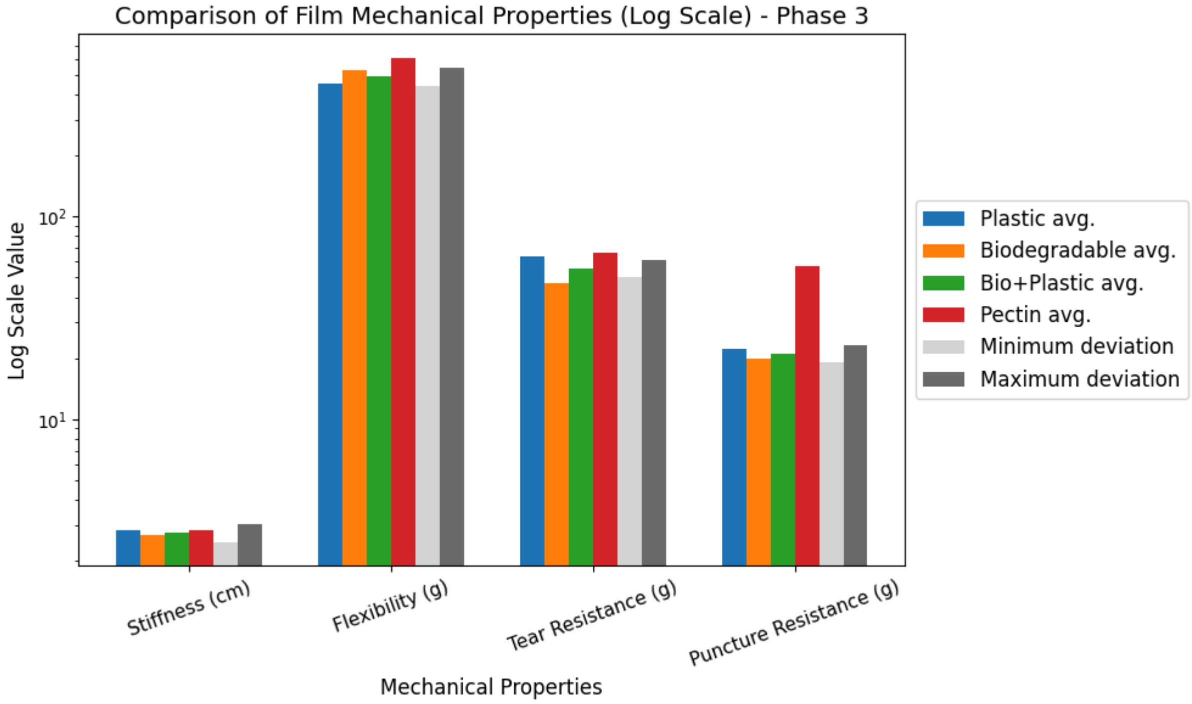
Despite these benefits, there can be a lot of harm if permeability is low. This is because of anaerobic bacteria. Certain anaerobic bacteria can turn nitrogen present in soil into polluting compounds such as nitrous oxide. If there is not enough gas (oxygen specifically) exchange, it can harm soil microbes and plants will not get nitrogen in the forms they need to grow. Hence, with a permeable film, it still allows for exchange of gases which can benefit soil aeration.

It is known that pectin is able to act as a hydrocolloid, swelling when it comes into contact with water. As a result, the pectin traps water which supports water retention.

The target permeability was 0%, however, the pectin film had an average permeability of 3.3% which may even be beneficial.

Mechanical Properties

	Stiffness	Flexibility	Tear resistance	Puncture resistance
Plastic avg.	2.83 cm	453.592 g	64 g	22.33 g
Biodegradable avg.	2.67 cm	529.2 g	47 g	20 g
Biodegradable +plastic avg.	2.75 cm	491.396 g	55.5 g	21.165 g
Pectin avg.	2.83 cm	604.8 g	51 g	56.67 g
Minimum deviation	2.48 cm	442.26 g	49.95 g	19.0485 g
Maximum deviation	3.03 cm	540.54 g	61.05 g	23.2815 g



Stiffness

Stiffness was measured as it is essential to the design. Mulch films need to be able to, with ease, wrap around the soil in agricultural soil. If the film is too stiff, this ability is compromised. As determined in the previous section, the film was found to be immensely thick, far surpassing the target range. It was recognized that this would likely increase stiffness and it did.

Stiffness was measured by assessing the overhand length of the film at 45 degrees. The determined target range for stiffness was between 2.48 cm-3.03 cm. The stiffness of the film was 2.83 cm. This was in the required range.

Flexibility

Flexibility is one of the most important factors in determining the functionality of an agricultural mulch film. The film should easily wrap around the soil for maximum effectiveness. If a mulch is not flexible enough, it compromises many of the benefits of a mulch film. For example, if the soil is not covered well, it does not trap water vapours and the film loses its benefit of improving soil moisture and water retention.

Furthermore, if a film does not cover the soil well, there may be pockets of exposed soil. In these areas, weeds are able to grow and the films' ability to prevent weeds is also compromised.

In this film, the flexibility did not meet the minimum target which was between 442.26 g-540.54 g. The film had an average flexibility of roughly 604.8 g which exceeded the maximum deviation by 11%.

The film had more flexibility than the previous trials likely because of the added methylcellulose concentration which improves its resistance to force. Before, pectin was the main film-former used. However, it was important to use the strength of the methylcellulose to ensure the strength of the film.

Tear Resistance

Tear resistance showcases how a film is able to resist a tear from continuing after being started. Tear resistance needs to be balanced. On one hand, low tear resistance can impair durability. However, if tear resistance is too high, it will be difficult for farmers to adjust the film size for certain conditions. Furthermore, if it is too strong, it will not degrade in adequate time.

Tear resistance was measured by evaluating the amount of weight required to continue a tear. The determined target range for tear resistance was between 49.95 g-61.05 g. The actual tear resistance was 51 g. This met the deviation.

Puncture Resistance

Puncture resistance shows how easily the film is susceptible to punctures, or holes. This is important to assess as mulch films are especially susceptible to holes on irregular or rough soils.

Tear resistance was measured by evaluating the amount of weight required to create a puncture. The determined target range for puncture resistance was between 19 g-23 g. The actual tear resistance was 56.67 g. This was 84% higher than the maximum target puncture resistance, meaning the film exceeded this factor.

The reason for this is likely the fact that the added methylcellulose concentration was able to resist punctures due to its rigidity.

Section 4: Summary

In the end, the final film met or exceeded many physical and mechanical properties which strongly indicates it has similar effectiveness to conventional films. Tests on plants can help further validate these results. The main objective, lower leachate toxicity was also met, with strong evidence to support this conclusion as seen with the seed germination bioassay.

Conclusion

In the end, an effective alternative to conventional biodegradable and plastic films was developed with lower leachate toxicity. This project has many applications. Firstly, most obviously, it allows increased crop yields through the benefits of a mulch film such as moisture retention and weed suppression. This film allows these benefits without compromising soil health through unsafe or underresearched leachates. Secondly, the use of this film reduces the accumulation of microplastics. Furthermore, through the benefits of a mulch film, this project can save water long-term through reduced water evaporation. Finally, this film also has a potential application in saving food waste. In Canada, nearly 60% of food produced is wasted and much of this ends up in landfills. This project presents a potential of reusing food waste such as citrus peels and pineapple peels in creating a more environmentally friendly mulch film.

Future directions for this project:

- Improve film properties in aspects where it has limitations.
  - Especially through using lab-grade or industrial methods.
- Conduct real-world trials on crops.
- Determine long-term impacts on crops.
- Conducting research on the films' scalability.
- Evaluating the impact of different film colours.

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I would also like to acknowledge that AI-use in this project was limited to surface-level research and understanding. Important details were taken from reputable articles. AI was also used for efficiency in creating certain graphs. However, everything was verified for accurate visualization of the data.