



Synthesis of polymer from biowaste (potato peel) and its biodegradability testing

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<p>Abstract:</p> <p>This thesis is about making bioplastic films from potato starch and testing their biodegradability. Three types of films were made. Firstly, starch extracted from potato peel in the laboratory was used to make one set of biofilms. For comparison, bioplastic films were also made from commercial potato starch and a mixture of commercial potato starch with laboratory-derived potato peel starch. All bioplastic film samples were made by mixing and heating starch with distilled water, 98% glycerin and vinegar at 100°C. Later, the films were dried at room temperature. Afterwards, the films were buried for 30 days in either a soil environment or in a domestic composter to test their biodegradability. The films that were made from lab-made starch degraded more compared to the films made from commercial starch and mixed starch. Based on the weight loss report, every sample showed promising results. Two samples that were buried in the soil were degraded completely as only labels were found. In addition, the absorbance peak of the functional groups of the samples each before and after biodegradability tests were located by FTIR analysis.</p>	
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List of Abbreviations

ABS.....	Acrylonitrile Butadiene Styrene
CH ₃ COOH.....	Acetic Acid
C ₃ H ₈ O ₃	Glycerol
CH ₄	Methane
CO ₂	Carbon dioxide
H ₂ O.....	Water
MgO.....	Magnesium Oxide
NO ₃ ⁻	Nitrate
PE.....	Polyethylene
PP.....	Polypropylene
PET.....	Polyethylene Terephthalate
PS.....	Polystyrene
PLA.....	Poly(lactic Acid)
PHB.....	Poly(hydroxy butyrate)
PEG.....	Poly(ethylene glycol)
PHB.....	Poly(hydroxybutyrate)
PHBV.....	Poly(hydroxybutyrate-co-hydroxyvalerate)
SO ₄ ²⁻	Sulphate
TPU.....	Thermoplastic polyurethane

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FOREWORD

Firstly, I would like to pour gratitude specially towards my supervisor Stewart Makkonen-Craig for supervising and letting me do this very important project. In addition, I appreciate the patience shown by him throughout the time of the project. On the other hand, I would like to thank Rasmus Björkvall for assisting me in the laboratory work.

Lastly, thank you all my friends, teachers, and staffs at Arcada who encouraged throughout this journey.

1 INTRODUCTION

1.1 Background

Petroleum-based polymers and plastics have been in use across the globe for a long time. When we say ‘petroleum-based polymers’, a distinct thing comes into our mind, i.e., plastics and other polymers essentials that we use in our daily life. The plastics are not only limited to individual uses. Most of the global leading companies, that manufacture things that we use in our daily lives are petroleum-based plastics. Usage of these plastics is one of the vital problems that the world is facing today. The reason behind the occurrence of this problem is the resistance ability of these kind of plastics towards degradability (Anon, 2017).

Basically, the materials are made up of long repeating chains of molecules that are known as polymers. Carbon chains play important role in forming polymers. The daily life products that we use, for instance, headphones, plastic bags, water bottles, pens, etc. are all made of polymers. In fact, almost everything that we touch and use in our daily life are polymers (Bradford, 2017). The problems do not lie in the usage of these kind of products. The problem is, how we use them and how we act when we do not have to use them anymore. The main environmental problem that we talk about today is the increasing greenhouse gases. Polymers can live up to hundreds of years in soil and water. We can imagine the amount of plastic products used by us and the amount of plastic wastes present in the environment.

On the other hand, if we see the date of plastic consumptions, around 300 million tons of plastics were consumed worldwide in 2015 (Arikan & Bilgen, 2019). We can assume the amount of plastic wastes found in soil and aquatic environment. If the consumption is high, the decomposition will be low which leads to plastic waste persisting in the environment. One of the disadvantages of using petroleum-based plastics is that it stays in the surrounding for very long time which has adverse effect in the ecosystem because it cannot be degraded microbially. In addition, the production of these polymers is also directly related to fossil fuels. As we know, fossil fuels are limited. These factors result in the increment of costs of fuels and its availability (Ghanzarbadeh & Hadi, 2013). We can see

the pictures and videos, for example, the beach filled up with plastic bottles and waste, aquatic animals wrapped with plastic bags, all over the news and social media.

Well, that is not the nature we and other animals want to live in. So, to overcome these problems, an option can be considered, e.g., usage of biodegradable polymers. The first idea and production of biodegradable polymers was introduced in 1980 (Markit, 1998). In addition, with the concern of drawbacks regarding the effects caused by synthetic plastics, scientists across the world came up with an idea to introduce the usage of bio-based polymers. Bio-based polymers are basically plastics that are made from renewable sources rather than the fossils and fuels which was mentioned above. Bioplastics are vulnerable in different forms. For example, the difference in pH and temperature, oxidation and reduction, reactions shown against different microorganisms etc. All these forms help bioplastics to further degrade into tiny and non-harmful things like carbon dioxide, methane, and water etc. So, biodegradable polymers are be considered to produce bags, packaging tools, agricultural tools which are some of the most used plastic forms (Shah & Vasava, 2019).

1.2 General objectives

Testing biodegradability of manufactured bio-based plastics is the main objective of this thesis. On the other hand, this thesis focuses mainly on prolongation of sustainability of plastic-based materials. Firstly, the project was supposed to be completed using fruit peel waste. However, after research was done, and with the recommendation from the supervisor, potato peel as the source of starch was finalized. On the other hand, the biodegradability test was supposed to do using the composter but the place where composter could be used was far away from where I live. So, the biodegradability test was done using a commercial Bokashi composter (domestic). Moreover, the testing was also done in a normal soil environment in a park nearby.

Research on potato productions and its found starch was done. In addition, bioplastics are made in the lab and its biodegradability testing was done. And the result obtained was conclude the thesis.

Furthermore, the conclusion of this thesis will depend upon the comparison made between the bioplastics made and the results that are obtained after the biodegradability testing.

This thesis has a total of six chapters in it. The introduction part will cover up the basic knowledge about bioplastics, petroleum-based plastics and the environmental impacts of petroleum-based plastics. On the other hand, the literature review will cover up the classification of plastics. In addition, the production of bioplastics from different types of biomass extraction and their usages will be covered. The part will also give a review about the basic details and facts about the scenarios of production and usages of bioplastics around the world. Furthermore, potato peel as the main source of starch, the application of bioplastics, sustainability and circular economy, importance and challenges of bioplastics are explained in the literature review.

Moreover, the details about the experimental procedure of making biofilms from potato starch are explained in the third chapter of this thesis and all the laboratory experiments done in the lab of ARCADA UAS are explained in details. On the fourth chapter, results obtained from the lab-work and after biodegradability testing are shown with pictures and tables. Finally, on the fifth chapter of this thesis, discussions about the project are written.

2 LITERATURE REVIEW

This chapter will cover up the details about bioplastics, their types, production and usages. In addition, the scenarios and data of the production of bioplastics all over the world are mentioned. Furthermore, the application of bioplastics, potato peel and sustainability are discussed.

2.1 Plastics

2.1.1 Classification of plastics

- a) Conventional plastics: These are the types of polymers which are made up of non-biodegradable fossil fuels. In other words, they are also known as petroleum-based plastics. For instance, Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET), Polystyrene (PS), and Acrylonitrile Butadiene Styrene (ABS) (Kripalani, 2020), these are the polymers that world uses every day. However, these types of plastics are non-degradable due to their unbreakable polymer chain in most natural conditions.
- b) Bio-based and non-biodegradable plastics: The plastics that made by mixing regular Polyethylene and plant-based polyethylene (PE) are bio based but non-biodegradable plastics. These types of polymers are made, for example, by adding 30% of plant-based PE in 70% of regular PE. PE from sugarcane is extracted as plant-based PE. These kinds of polymers are widely used today as an alternative to petroleum-based plastics. However, it does not decay biologically. The advantages of these polymers are that unlike the petroleum-based plastics, it does not emit greenhouse gases (Kripalani, 2020).
- c) Biobased and biodegradable plastics: So, this thesis is all about biobased and biodegradable plastics. These materials are usually made up of starch and cellulose. It is fully plant based. That is why, after its usage, even if a person throws the plastics away, it decomposes over a short period of time. These kinds of polymers can be used for packaging, making toys etc. as most of the biowastes come from these materials. For example, Polylactic acid (PLA) and starch-based compounds are used in making biodegradable plastics (Kripalani, 2020). Figure 1 below

shows the preference of biobased biodegradable plastics over petroleum based plastics.

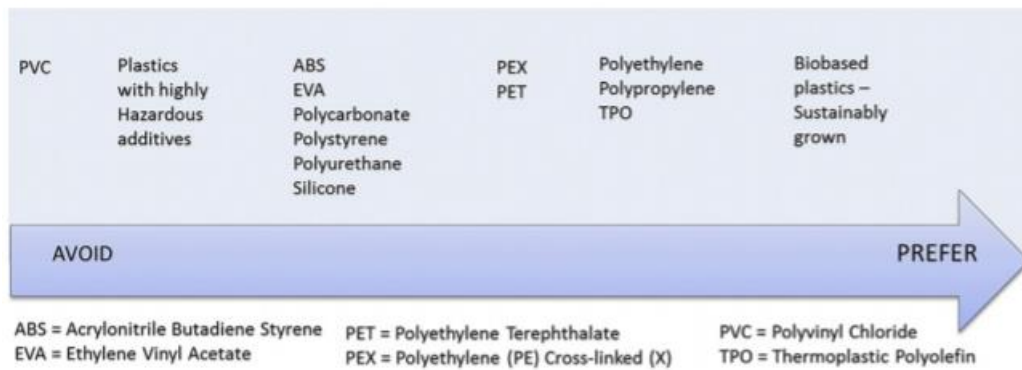


Figure 1: Preference of biobased biodegradable plastics over petroleum-based plastics

- d) Oil based and biodegradable plastics: these polymers have been in use for a long time. However, most of the usages of these are done in tissue engineering and biomaterial applications (Kripalani, 2020).

The figure 2 below gives us precise knowledge about polymer classification.

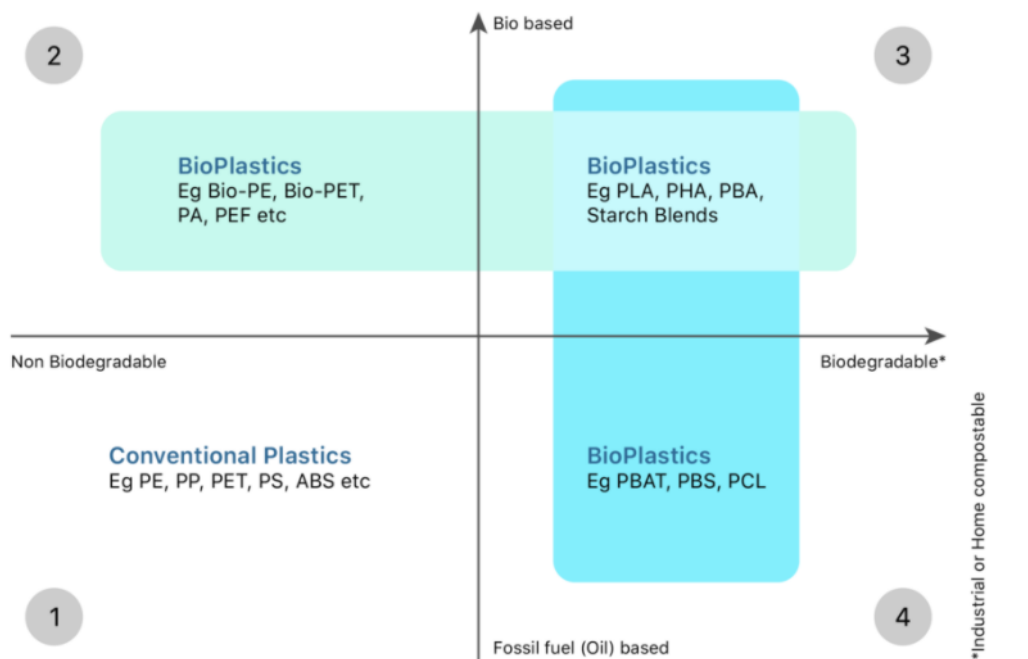


Figure 2: Polymer classification (Kripalani, 2020)

The figure 3 below shows the datasheet of different kinds of plastics produced globally in 2019.

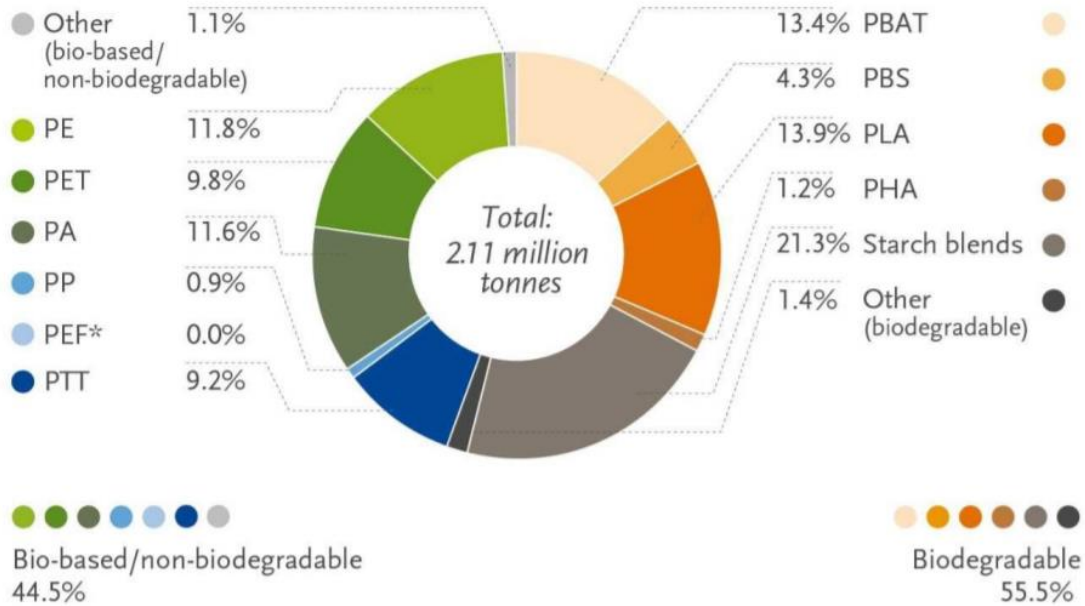


Figure 3: global production of bioplastics (2019) (Agrahari, 2020)

2.2 Bioplastics

To understand the precise meaning of bioplastics, one must understand the term bio. So, bioplastics are polymers that are manufactured biological sources. To understand it simply, bioplastics are manufactured directly from biological sources. For instance, starch from fruits and other vegetables are used for many purposes. Manufacturing bioplastics is one of the uses.

The combination of different materials makes a huge family to form a bioplastic. Not all biopolymers are the same. Different bioplastics possess different types of chemical properties. Either a bioplastic is biobased, or it is biodegradable, or it possesses both properties (bioplastics, 2018). When we talk about bioplastics, especially this thesis mainly focuses on biodegradable bioplastics, biodegradable biobased plastics should be taken into huge concern.

The biodegradability of a bioplastic depends upon the nature of formation. For example, many bioplastics that have been in use today are made up of 20% or more renewable

sources. Compared to petroleum-based plastics, these bioplastics are more reliable towards decomposition. However, recent studies shows that even if the modern bioplastics are in use, it is not 100% decomposed into nature (Cho, 2017).

For example, to know different types of plastics and their nature of decomposition, it can be classified into three types. The types illustrated below are not exactly the types of bioplastics, however, to make it easy to understand, the followings are classified.

2.2.1 Common bioplastics derived from biomass extraction

Starch-based polymers are the most common bioplastics used globally. However, bacteria and fungi produce more complex polymer structures with more than one type of carbohydrate unit. These polymers contain enzymes which helps in hydrolysis reaction making it easy to decay. Below are the different classifications of it:

Thermoplastic starch

The crops like potato, corn and rice are rich in starch. Starch is produced in tiny granules which has many applications in medical fields as well. The reason behind using thermoplastic starch for extracting biobased biodegradable plastics is it is rich in proteins and lipids which is easier for microorganisms to decay and when it comes in touch with oxygen, it becomes rapidly saturated. On the other hand, the starch-based bioplastics decomposes into harmless microplastics and decays soon when it comes in touch with the soil and water (Ghanbarzade & Almasi, 2010). Molecular structure of starch is shown in figure 4.

Starch

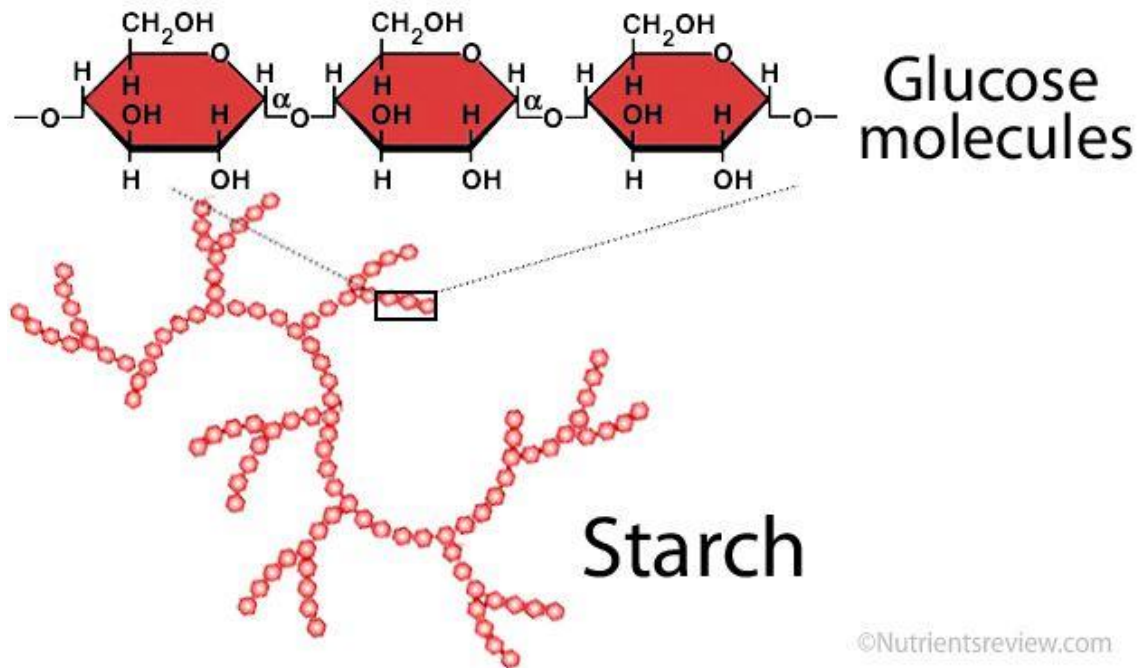


Figure 4: molecular structure of starch (Ghosh, 2020).

Cellulose

With worldwide estimated production of 1.5×10^{12} tons, cellulose is one of the most produced polymers among the available ones. Because of the presence of lignin in cellulose, it is highly attacked by microorganism. This behavior of cellulose has gained attention and is one of most researched polymers. it is widely used in paper, textile, and wood industries (Ghanbarzade & Almasi, 2010). Chemical structure of cellulose can be seen in figure 5 below.

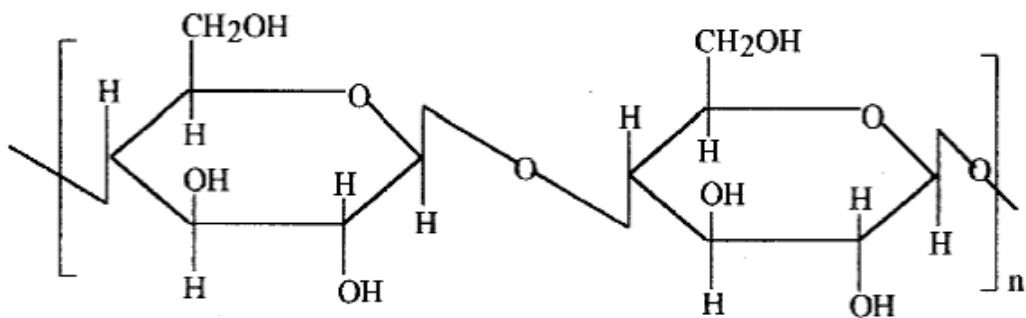


Figure 5: chemical structure of cellulose (Ghanbarzade & Almasi, 2010).

Fibers

The plant based natural fibers are rich in cellulose, hemicellulose, lignin, and pectin. Lignocellulose is the most abundant biomass found in nature as it is produced 50% of the global biomass. To produce daily used products like paper, lumber, and even biodegradable polymers, the lignocellulosic has the potential to cover it (Ghanzarbadeh & Hadi, 2013). The structural organization of fiber cell wall is shown in figure 6.

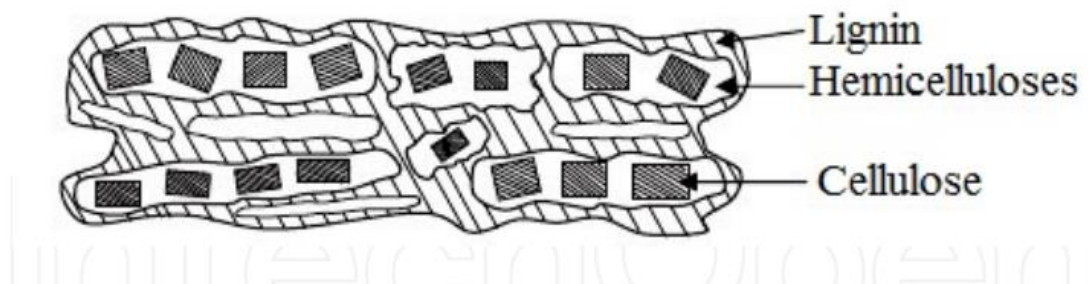


Figure 6: structural organization of fiber cell wall (Ghanzarbadeh & Hadi, 2013).

Chitin and Chitosan

In the shells of crabs, lobsters, shrimps and even in insects, a polysaccharide is found which is known as Chitin. It can also be prepared by the fermentation process of fungi. However, the deacylated derivative of chitin is chitosan. The biocompatibility nature and its antimicrobe activity of these biopolymers help them to absorb heavy metal ions. These

are widely used in cosmetic industries as the polymers have the property of retaining the water. However, the heavily deacylated Chitin has slow biodegradable rate but if chemical modifications are done, the rate can be increased (Ghanzarbadeh & Hadi, 2013). The chemical structure of chitin and chitosan is shown in figure 7.

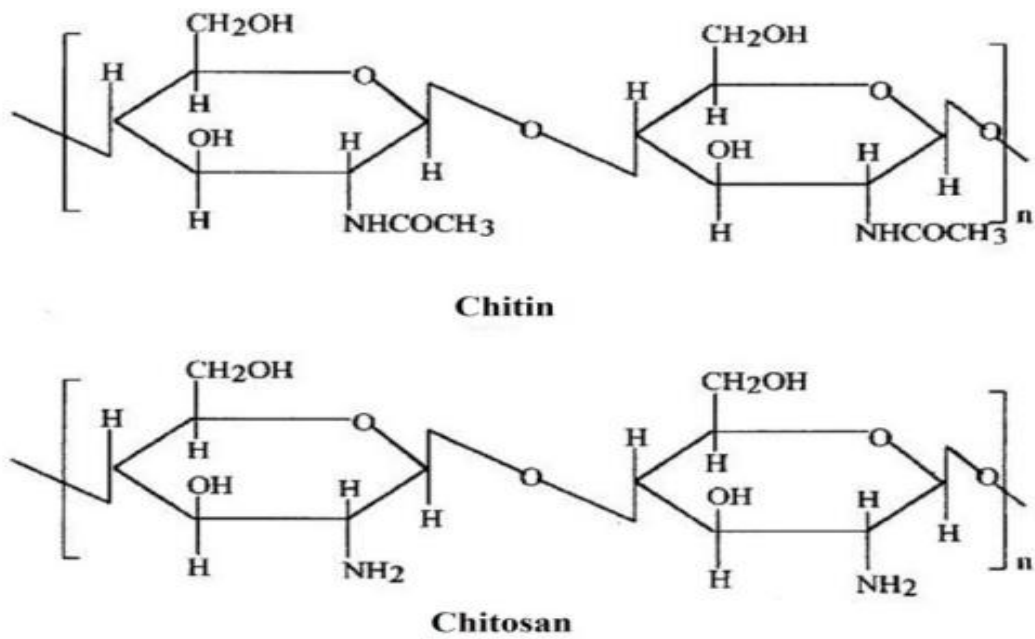


Figure 7: Chemical structure of chitin and chitosan (Ghanzarbadeh & Hadi, 2013).

2.2.2 Global scenario of production of bioplastics and its uses

As of 2019, about 1% of the total plastics produced (in tons) were bioplastics. In 2019, about 360 million tons of plastics were manufactured. About 2.11 million tons were bioplastics. (bioplastics, 2020). With increase in the demand of plastics every day, the productions have also been increased drastically and so the pollution. Even though, the total production has been seen increased, still, with the given statistics, the world is suffering. For example, most of the European nations have adapted to manufacture materials like take away bags, trash bags from biobased polymers. However, usage of petroleum-based plastics can also be seen in many countries (Pei & Schmidt, 2011). With the increased concern towards climate change, the nation's interests on manufacturing bioplastics have also been increased. The figure 8 below shows the data of bioplastics production relative to other petroleum-based plastics:

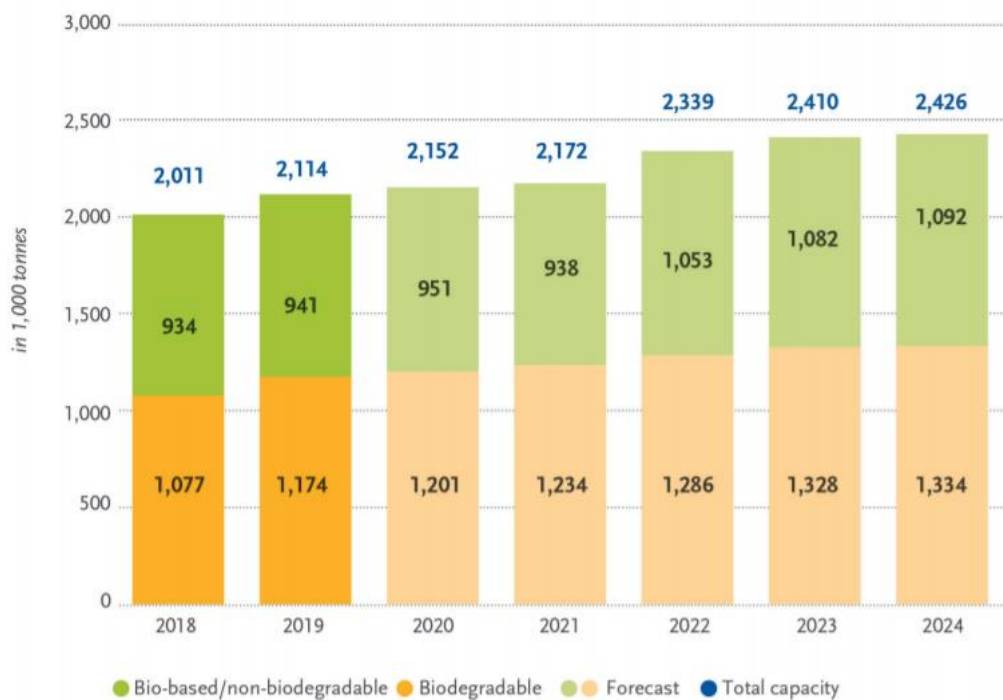


Figure 8: global production capacities of bioplastics (2019-2024) (bioplastics, 2020).

2.2.3 Application of bioplastics

Sustainable production and consumption of materials have been a challenging task to do. In order to reduce the usage of petroleum-based plastics, bioplastics have been playing important role to replace the usage of petroleum-based plastics.

Some of the applications of bioplastics are illustrated below:

Food packaging

One of the common and highly adapted application of bioplastics is food packing. To reduce the emission of carbon dioxide and dependency on fossils, using of recycled materials and reusing plastics are being done. However, more efforts can be made towards more energy-efficient process. Through the enzymatic action of microorganisms, biodegradable polymers are capable of decomposing into CO₂, CH₄, H₂O and other inorganic compounds. Hence, the food industries over the world are interested in using bioplastics for food packaging (Peelman *et al.*, 2013: pp.128–141).

Medical purposes.

An annually growing plant named flax has a great significance in medical industries as well. For example, by genetically modifying flax genome, the flax properties can be improved and can be used in the medical industry. Biomechanical properties of flax fibers can be improved by introducing polyhydroxy butyrate (PHB) genes from *Ralstonia eutropha* into the genome of flax. The modified fibers along with PHB make an important material in biomedical application. Different polysaccharide complex like cellulose, hemicellulose and pectin are contained in flax fiber. So, the quality of modified fabric can be used for dressing chronic wounds (Kulma *et al.*, 2015:pp.80–89).

Cosmetics

Cosmetic products that we use in daily life are easily decomposable. However, the materials that are used for packaging of cosmetic products are usually petroleum-based plastics that remains in the landfill for thousands of years. So, considering the properties of raw

materials that are used for packaging is vital. Some petrochemical based plastics such as Polyvinyl chloride (PVC), Polyamide (PA) etc. are widely used in cosmetic industries for the packaging of their materials as they are cost-effective and are found in abundance. On the other hand, the materials should have good fortification towards oxygen, carbon dioxide, anhydride, and aroma compounds. The common petrochemical-based polymers have good resistance capability towards them compared to biobased polymers. However, the most commonly used bio-based plastic i.e. Polylactic acid (PLA) is widely used as packing material as it has good biocompatibility (Cinelli *et al.*, 2019:p.26).

The mechanical properties of biopolymers are poor. In addition, the chemical resistance of biopolymers is low. So, to improve these properties, biopolymers can be reinforced with fillers. In this way, biopolymers composite can be created which has many applications. The table 1 below illustrates some of the biopolymer composites, their properties, and applications:

Table 1:properties and applications of biopolymer composites (Anon, n.d.)

Matrix/Filler	Properties	Applications
PLA/PEG/Chit	Low stiffness/ High flexibility	Bone & dental im- plants food packaging
PLA/Cellulose	Improved rigidity & bio- degradability	Packaging, automo- tive
PLA/Potato pulp	Low stiffness & ductility, good processability	Food packaging
PLA/MgO	Improved stability and bi- oactivity	Medical implants, tis- sue engineering, or- thopaedic devices
PHB/wood sawdust fi- bres	Improved degradation in soil	Agriculture or plant nursery
PHBV/TPU/cellulose	Balanced heat re- sistance, stiffness, and toughness	Food packaging tissue engineering

Nanocellulose/CNT	Good electrical conductivity	Super-capacitor, sensors
Rubber/potato starch	Accelerated thermal ageing	Vibration isolators, shock mounts, electrical components
Potato starch/wheat gluten	Improved maximum stress & extensibility	Development of bio-based plastics
Alginate/cinnamon oil	Good antibacterial activity	Active packaging materials
PVA/Chitosan	Good chemical stability	Drug delivery food packaging
PPC/TPU	Good thermal stability & stiffness	Electronic packaging applications

Formatting...

2.3 Potato as renewable source biodegradable bioplastics

This chapter will explain why waste from potatoes could be utilized in film making.

2.3.1 Potato Production and Waste Management

Potato is one of the most famous crops that is grown around the world. After maize, wheat, and rice, it is the most consumed and important crop as it is widely used (FAO, 2008). It is rich in its chemical compositions as all the compositions has its own value. Water, starch, protein, fiber, and fatty acid are the chemical compositions found in it (FAO, 2008). Due to the composition of starch in it, potato has become one of the vital crops not only for food industry, but its advantages in materials science as well.

Apart from the food industry, due to its importance in worldwide business, many byproducts are produced every day. Potato waste itself and its peels are the byproducts that are produced in food industry. Apart from biofuels, bio-fertilizers, biogas and other food activities, these byproducts are the waste which can be further processed chemically to manufacture biopolymers which helps in proper utilization of the waste and contribute to materials industry (Javed, et al., 2019). Figure 9 below shows the chemical composition of potato.

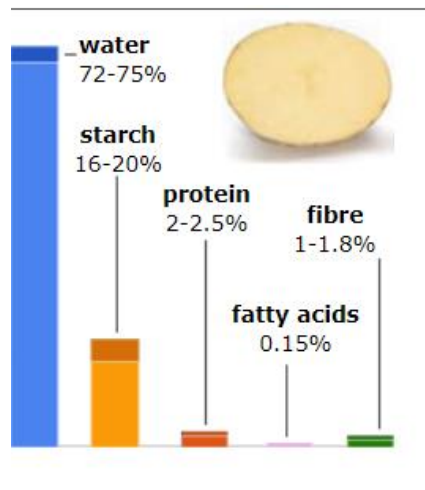


Figure 9: chemical composition of potato (FAO, 2008).

The figure above shows that about 22.5% of the vegetable is rich in starch and protein. As starch is highly rich in glucose molecules, the residue of potato can be used to manufacture bio-based biodegradable polymers.

2.4 Sustainability

In this chapter, sustainability usages of potato peel waste and a simple knowledge about circular economy is discussed.

2.4.1 Sustainable usage of potato peel

Well, potato is one of the largest consumed foods. However, the peel of potato is bio-waste, thus, can be used for various purposes. The cycle created between food itself and the waste determines the sustainability of the product. As such, sustainable application is one of the major concerns across the world the bio-based biodegradable polymers could play important roles in reducing plastic pollution (Dam, 2014).

On the other hand, reducing and reusing of petroleum-based plastics are being done across the globe to control the plastic pollution. However, there are some products such as take away bags and other toys are difficult to reuse. So, to overcome such problems, eliminating such single use products that can neither be recycled or decomposed and replacing them with bio-based biodegradable plastics obtained from potato peel could bring its sustainability (Álvarez-Chávez, et al., 2012).

The main reason to purpose sustainability in this thesis is to develop concerns towards addressing life cycle of the material, manufacturing the bio-based biodegradable polymers, and redeeming the materials after its use.

2.4.2 Circular Economy

Food industries such as potato chips industries produce tons of potato peel waste as it does not have any significance in food industries. The peels are discarded, and it causes environmental concern due to its microbial spoilage. So, either the peels are used for

fertilizers or animal feeds which are low in value. This leads to a reduction in value of highly nutritive biomass. The properties like antioxidant, antibacterial and anti-inflammatory are possessed by the peel which can be used in many alternative ways like producing biopolymers rather than using it for feedstocks or fertilizers (Liand & McDonald, 2014).

Worldwide, potato-based industries produce almost 140 thousand tons of potato peel every year. Potato-peel recycling is one of the major topics discussed nowadays in bioplastics industry (Wu, 2016). For example, production of biogas, alkaloid extraction, extraction of lactic acid for cosmetic purposes, extraction of phenolic acid etc. are done using the potato peel waste. However, researchers today are focused on utilization of the biomass more, where the sustainable cycle between the wastes and products could be done as it can play a vital role in environmental aspects (Wu, 2016).

To create economic feasibility along with the sustainability of the environmental, biorefinery concept for the extraction of valuable compounds from the biomass to produce marketable outcomes are done (Mania, et al., 2017). Figure 10 illustrates the concept of circular economy to enhance sustainability of the environment.

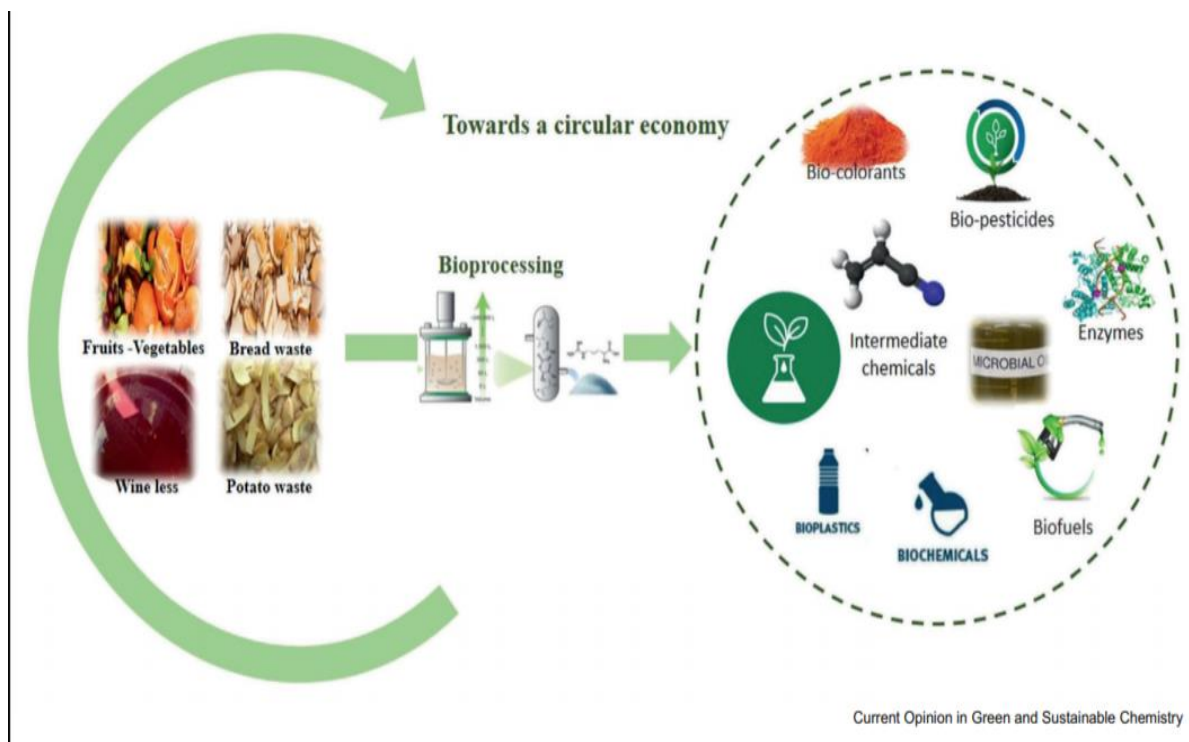


Figure 10: Bioprocessing of food waste for value-added products production (Mania, et al., 2017).

2.5 Polymer biodegradation

Microorganisms such as bacteria, algae and fungi conduct metabolism activities to the polymers which results in the production of carbon dioxide (CO₂), methane (CH₄) when oxygen is not present, and the residues. This process is known as biodegradation of polymers. To produce these degradation products microorganisms come into action. However, it is only possible for a polymer to biodegrade if the polymer is degradable. The petroleum-based polymers that are being used in daily life are unlikely to biodegrade which results in environmental pollution as it takes thousands of years to decay. So, for proper waste management options and to manufacture biodegradable plastics, worldwide researches are going on (Serwańska-Leja & Lewandowicz, 2010:vol.19).

To be able to understand the biodegradation processes of polymers and their environment impacts have been vital. Direct and indirect approaches have been done by using different analytical approaches to study the biodegradation of polymers. The degradation of polymers is evaluated by different visual observations such as weight loss measurements, mechanical properties' changes, and changes in molecular weight. However, proper demonstration of biodegradation is unlikely possible with these types of measurements. Thus, respirometry methods are used to measure the biodegradability of the polymers (Castro-Aguirre *et al.*, 2017:pp.251–271). Aerobic and anaerobic biodegradation are the processes in polymer biodegradation.

Basically, in aerobic biodegradation, the evolved CO₂ when microorganisms react with polymers waste in presence of oxygen is measured which results in proper assessment of biodegradability (Castro-Aguirre *et al.*, 2017:pp.251–271).

Whereas in anaerobic biodegradation, methane (CH₄), water and biomass are the byproducts as the reaction occurs in oxygen free environment. Since, the whole anaerobic biodegradation process occurs in absence of oxygen, the organic matters act as electron donor. In anaerobic process, electron acceptors like nitrate (NO₃⁻) and sulphate (SO₄²⁻) are required (Quecholac-Piña *et al.*, 2020:no.1).

Regardless of the production of bioplastics from different sources, all the products look similar to the naked eyes. So, a series of tests and certifications should be followed for different kind of bioplastics. On the other hand, the standard time duration set for biodegradability testing should also be considered. The standard time for the test usually are between 14 days and 24 months. However, to reduce the cost of laboratory spaces and

equipment and to speed up the process, higher temperature is often used than the standard one. The standard time used for the test, percentage of biodegradation and analytical method with standard can be shown in the figure 11 below:

Biodegradation	Minimum degradation [%]	Timeframe of degradation	Maximum test duration	Analytical method	Standard
inherently degradable	70	within maximum duration	14 days	DOC or BOD analysis ^[a]	OECD 302B or 302 C
readily degradable	60	10 days ^[b]	28 days	CO ₂ evolved or O ₂ demand	OECD 301, 306, 310
ultimately degradable	90	within maximum duration	6 months (aqueous); 24 months (soil, seawater/sediment)	CO ₂ evolved or O ₂ demand	ISO 14851, 14852 (aqueous), ISO 17556 (soil), ISO 19679, 18830 (seawater/sediment)

[a] DOC: dissolved organic carbon, BOD: biological oxygen demand. [b] Only after 10% degradation is reached.

Figure 11: Difference between types of biodegradation tests

The compost environment also plays a vital role in biodegradability testing and there are certain certifications for composting. For example, products that can be composted in food waste is certified by ‘OK home compostable’ which is certified for low temperature degradation and for mobile home compost. On the other hand, the industrial facility composter is certified by ‘OK compost IND’ as there could be some products that needs to be composted in industrial facility. (Filiciotto & Rothenberg, 2020)

2.5.1 Global Importance

With the extreme usage of non-renewable resources, the industrialized countries were developed economically. With the limited non-renewable resources today, and with the increment of its costs, renewable vegetal resources are the alternative solutions for sustainable development. With the development of biodegradable bioplastics, sustainable management of the resources has been possible to create ways in the field of agriculture, chemistry, and plastic engineering. The waste production reduction and waste management are also possible because of their biodegradable nature (Anon, n.d.).

Some of the importance of biodegradable bioplastics are:

1) Lesser carbon footprint

Unlike petroleum-based plastics, biodegradable bioplastics do not have carbon footprint as the biodegradable polymers are plant based which results in lesser dependency on limited non-renewable petroleum-based plastics. The oil-based plastics uses a lot of energy and releases massive amount of CO₂ while manufacturing petrochemical building blocks for fossil-based plastics (Anon, 2020a). Annual emission reductions of above 42 million tons of CO₂ would be realized if bio-based plastics are to substitute the fossils-based plastics (Anon, n.d.). Carbon cycle of bioplastics can be seen in Figure 12 below.

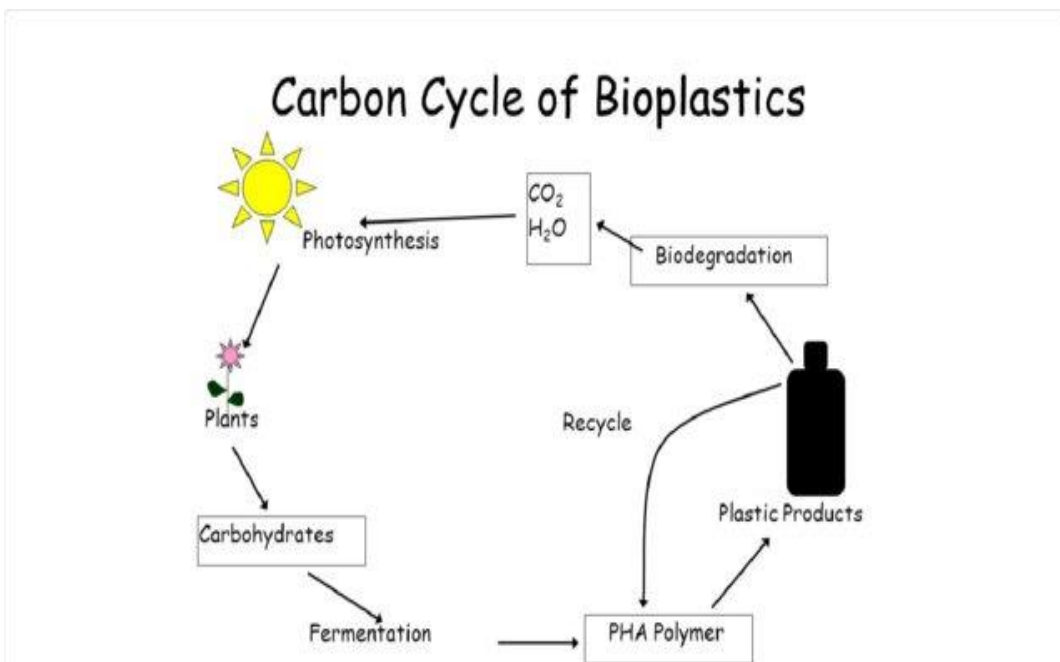


Figure 12: carbon cycle of bioplastic (Bharti & Swetha, 2016)

2) Climate change

With the increase greenhouse gases in the atmosphere, bioplastics could help reduce the gases which helps in reducing the average temperature in the atmosphere resulting control in the number of thunderstorms, flood, and annual precipitation (Anon, n.d.). As biodegradable plastics do not rely on oil or petrol as its primary, manufacturing ingredients, the carbon emission is likely to be reduced and help fighting against global warming (Ferro, n.d.). According to Anon, 2020b, two different scenarios have been made i.e., firstly, one gigaton of carbon emissions would be cleared of if production of bioplastics would be 12% of the total plastics supply. On the other hand, 3.8 gigatons of carbon emissions could be avoided if the market is to reach up to 46% (Ferro, n.d.).

To recapitulate the global importance of biodegradable plastics, evaluation of environmental impacts from bioplastics must be done. Life cycle assessment (LCA) is one of the major methods to do so. From the raw material to the final use of bioplastics, each assessment is made to evaluate the environmental impact of bioplastics through LCA. According to a study, with the substitution of 20% PET bottles with PLA bottles, there was a significant reduction in greenhouse gases (Atiwesh *et al.*, 2021:p.e07918).

2.6 Challenges

In addition, with the significant advantages of bioplastics, there are some challenges that have to be considered as well. So-called biodegradable plastics like PLA, which is used for manufacturing bioplastics products, the degradability is determined by the additives making the final products. It becomes a threat to the environment as the microplastics created from the degradation of additives do not decompose completely (K & Booth, 2017). On the other hand, the fertilizers and pesticides used for growing crops result in producing more pollutants while manufacturing and chemical processing bioplastics which should be considered. On the other hand, not many cities have enough infrastructure to store the biowastes to produce bioplastics as the wastes end up in land resulting in methane gas release (Cho, 2017).

2.6.1 Economic challenges

There are economic challenges with the production of bioplastics as well. Due to the high manufacturing cost, expensive polymer plant production, production in small scale and the cost of raw materials, the final product of bioplastics could be heavily expensive compared to petroleum-based plastics. Unlike petroleum-based plastics, the applications of bio-based plastics are relatively less. Thus, global adoption of bioplastics could be a challenge (Raushan Karn, 2022).

Furthermore, due to low melting point, low transparency, low tensile strength and its brittleness, the applications are limited thus affecting in economic consideration (Raushan Karn, 2022).

3 EXPERIMENTAL PROCEDURE

The details about the experiment procedure about making biofilms and biodegradation process is explained in this chapter.

3.1 Production of bioplastic film

The experimental procedure involved in this thesis' laboratory work is based on the experiment reported by (Arikan & Bilgen, 2019). Firstly, the potato starch is extracted from wet potato peels. In addition, the wet starch is put to dry for two hours at 50°C. Afterwards, the obtained potato starch is mixed with tap water at the amount of ratio 1:10. While the starch and tap water are being mixed, 16.2 mL of vinegar and 10.8 mL of glycerin are mixed as well.

Long chains of glucose molecules join to form starch. Two main polymers are contained in the starch: amylose and amylopectin. Amylose is straight chained, and amylopectin is branched. Moreover, the polymer amylose is straight chained. Even though the straight chained line up together nicely to make a good film, the output becomes brittle. Some areas of the film might become crystalline and cause brittleness. That is why glycerin will be used. As glycerin is hydroscopic, it prevents the mixture from forming crystalline areas which inhibits brittleness and give it more plastic properties (RSC, n.d.). Figure 13 and 14 shows the importance of glycerin to prevent the films from getting brittle.



Figure 13: brittle product due to polymer chain link-up (RSC, n.d.).

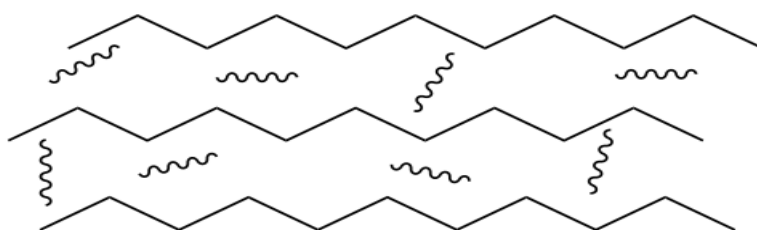


Figure 14: glycerin preventing chains from lining up (RSC, n.d.).

The overall step-by-step procedure previously done by (Arikan & Bilgen, 2019) which is later followed in this experiment can be shown below:

1) Extraction of potato starch from peel.

Firstly, starch is extracted from wet potato peel by blending the mixture of water and peel. Moreover, the mixture is rinsed by water and the starch will be extracted at the bottom of the beaker. After rinsing it multiple times, and after starch is seen at the bottom of the beaker, water is evaporated, and then dry starch is extracted after two days of evaporation (york, n.d.).

2) Mixing ingredients

13.5 mL of starch is mixed with 135 mL of tap water in a beaker. Afterwards, 16.2 mL of Vinegar (acetic acid) is added along with 10.8 mL of glycerin.

3) Heating the mixture

The mixture is heated in beaker using magnetic stirrer for 20 minutes at 100°C with continuous monitoring.

4) Making film

After the mixture is heated, the mixture is placed in petri dish and let dry for 24 hours at 50°C, and finally the formed bioplastic film is extracted from the dish.

3.2 Biodegradation process

The standard method for biodegradation process was not followed because the industrial waste dumping site could not be managed as it was far away from the city. However, a composter that is used in garden for fertilization of plants was bought from a local Class Ohlson market and biodegradation was done at home. The results were good in terms of what this project has demanded.

So, the film samples were buried in moist soil and composter for four weeks. And weight lost measurement was done after the biodegradation time. Due to the biological activity

by enzymatic reaction, it leads to the change in chemical structure of the film after it is buried into the soil which results in weight loss.

The percentage of weight loss was calculated with the weight of the product made and the weight of the bioplastic taken out after burying. It was calculated by the following formula.

$$\text{Weight loss (WL)} = \frac{\text{Initial weight (}W_i\text{)} - \text{final weight (}W_f\text{)}}{\text{Initial weight (}W_i\text{)}} \times 100\% \text{ (Arikan \& Bilgen, 2019).}$$

For the comparison, commercial bioplastics is buried in the same environment as the potato peel bioplastic and the weight loss of both plastics were compared.

3.3 Chemicals and materials used

3.3.1 Potato and potato peel

4.52 kilograms of potato (Peruna kiinteä pesty) was bought from S-market. All the potatoes were peeled to get 500.9 grams of peels.

3.3.2 Commercial potato starch (perunajauho)



Figure 15: perunajauho

Biofilms were made from commercial potato starch as well to compare the biodegradability against the biofilm extracted from lab-made potato starch. The molecular formula of potato starch is given below in Figure 16.

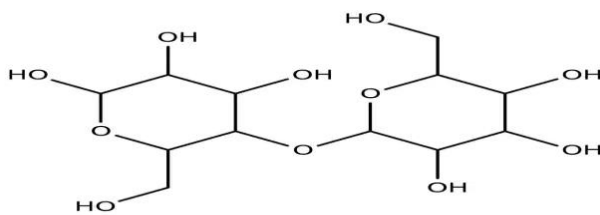


Figure 16: molecular structure of potato starch (scientific, n.d.)

3.3.3 Vinegar (Acetic acid) (CH_3COOH)

By the oxidation of ethanol, acetic acid is formed. However, vinegar is the mixture of water and acetic acid. Vinegar is widely used in seasoning food (Plessi, 2003). Acetic acid is sour, colorless and has pungent smell. Furthermore, as acetic acid has anti-bacterial and anti-fungal properties, it is often used for household cleaning purpose (Chant, 2017). The vinegar used for this experiment is below in Figure 17.

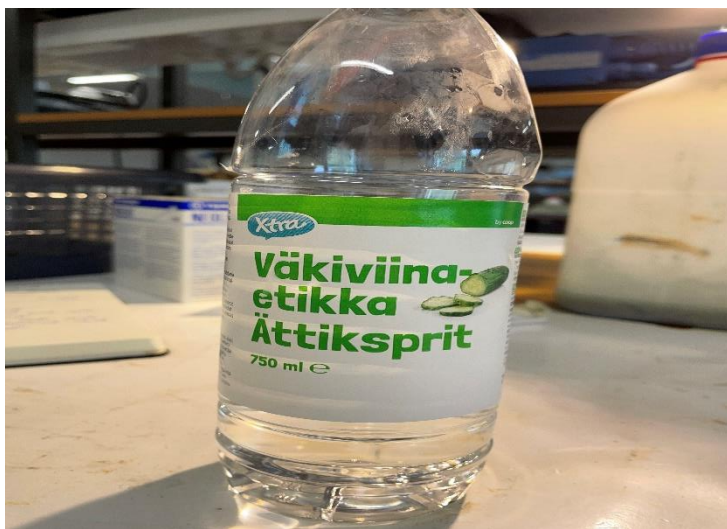


Figure 17: commercial vinegar

3.3.4 Glycerol (C₃H₈O₃)

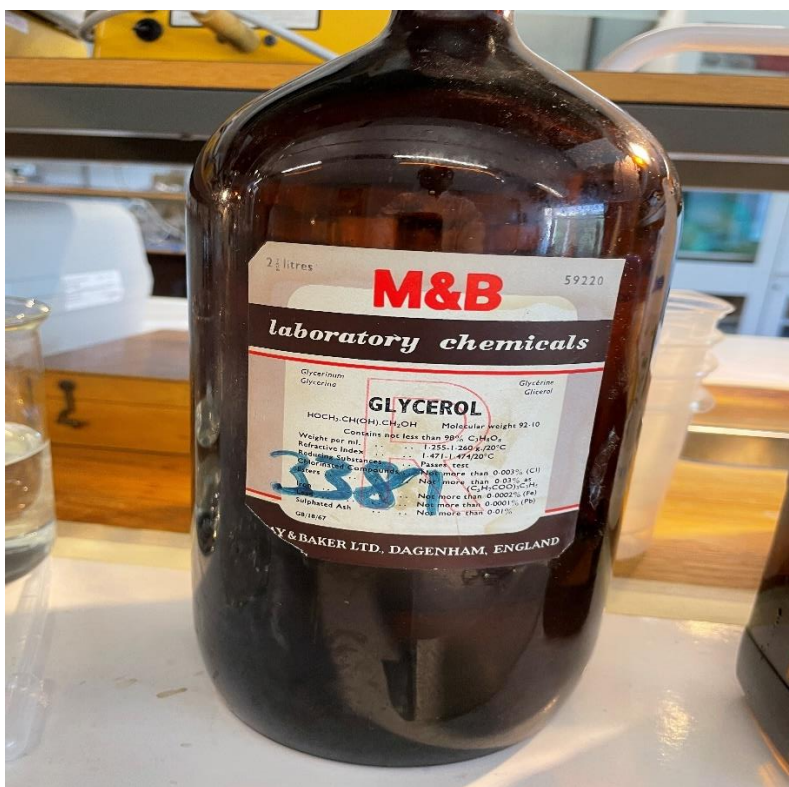


Figure 18: Glycerol

A naturally occurring alcohol, that is odorless and colorless which is used as solvent, sweetening agent and in medicine is called glycerol (WebMD, 2005). However, glycerol will be used in this experiment to prevent the film from being brittle. The glycerol used is shown in Figure 18 above.

3.3.5 Equipment used

- 1) Beakers
- 2) Potato peeler
- 3) Glass rod
- 4) Magnetic stirrer
- 5) Spoon
- 6) Petri dishes
- 7) Aluminum foil
- 8) Weighing scale (balance)
- 9) Tea strainer

3.4 Laboratory procedure

3.4.1 Extracting starch from potato peel

4.52 kilograms of potato were peeled to get 500.9 grams of peels. 400 mL of tap water was mixed with the potato peels to get the blending started. After the peels were blended, mashed potato peel was formed.

The mashed peel was rinsed and filtered using tea strainer four times using 200 mL of water in four beakers. The rinsing and filtration process were done until to get the maximum starch at the bottom of the beaker. After the rinsing and filtration was done, all the four beakers were kept constant for an hour to get maximum starch at the bottom of the beaker. Afterwards, the starch began to show up at the bottom of the beakers. The brownish water was then carefully poured into the sink, leaving starch at the bottom. After that, three beakers were rinsed with 100 mL of water each to mix all of the water-starch mixture into the fourth beaker. Furthermore, the only water-starch contained beaker was left for an hour more to let all the starch settle down at the bottom. Lastly, the brownish water was carefully poured into the sink to let the liquid evaporate and to get the starch settle down at bottom. The starch was put to dry in room temperature for five days. After, five days of waiting, dry whitish-brown starch was formed at the bottom of the beaker.

19 grams of starch was extracted from 500.9 grams of peel.

Figures 19, 20, 21 and 22 below shows the making of starch and how it settles down at the bottom of beakers.



Figure 19: starch settling down



Figure 20: the fourth rinsed starch beaker

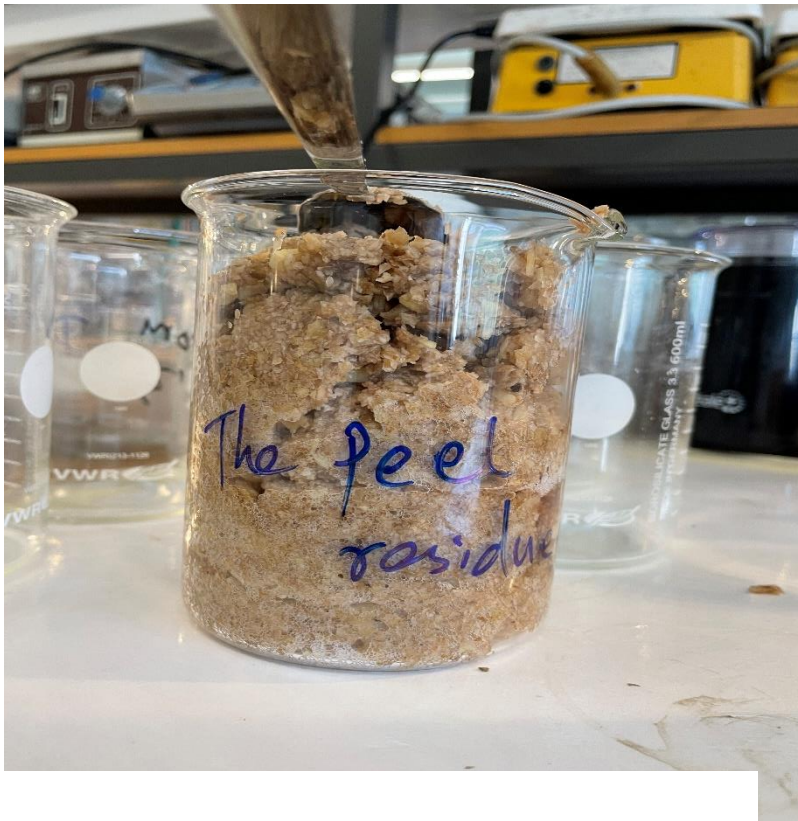


Figure 21: the peel residue

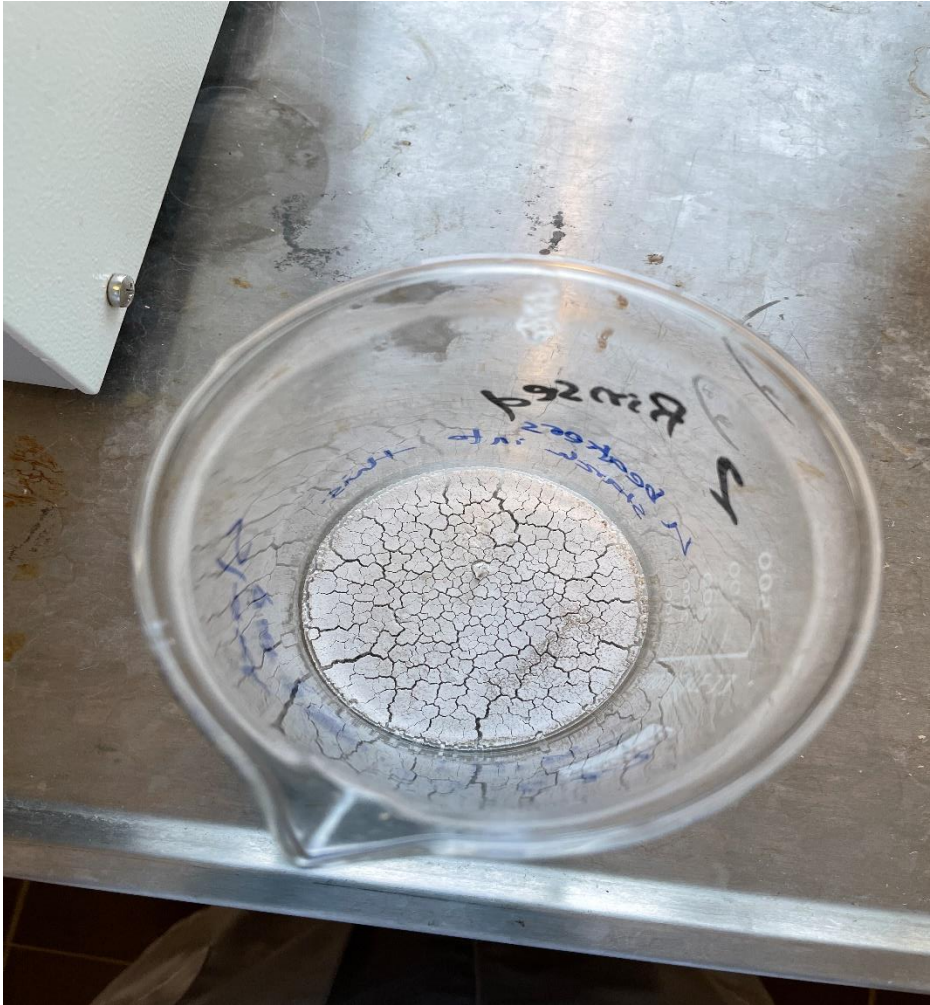


Figure 22: final starch (dried)

3.4.2 Making biofilm

Three different types of biofilms were made by using laboratory made starch, commercial starch and mixture of lab-made and commercial starch. The experiment procedure is done following the article written by (Arikan & Bilgen, 2019). A total of six batches of films were made using equivalent quantities of chemicals. Two samples for each batch were made to burry in composter and normal soil and then later compare the results. Figures 23, 24, 25, 26, 27 and 28 below show the films samples made from different starches.

a) Biofilm from lab-made starch.

13.56 grams of lab-made starch was mixed with 135 mL of distilled water in a beaker. The beaker was then put to magnetic stirrer. In addition, 16.25 mL of vinegar and 10.8 mL of glycerol was mixed in the beaker. The whole mixture was heated at 100°C for 20 minutes. After that, viscous liquid was formed, and it was put carefully and symmetrically in petri dishes. The biofilms were then put to dry in room temperature for 72 hours. 1.338 grams and 2.7737 grams of biofilms were produced.



Figure 23: biofilm sample A (1.3388g)



Figure 24: biofilm sample I (2.7737g)

b) Biofilm made from mix starch (lab-made + commercial starch)

5.27 grams of lab-made starch and 8.22 grams of commercial starch was mixed with 135 mL of distilled water in the beaker and put to heat. After that, 16.25 mL of vinegar and



Figure 26: biofilm sample B (11.7985g)



Figure 25: biofilm sample 2 (3.0933g)

10.8 mL of glycerol were added in the mixture. The mixture was then heated for 20 minutes at 100°C. after, the mixture got viscous, it was placed symmetrically in petri dishes. The biofilms were then put to dry in room temperature for 72 hours. 11.7985 grams and 3.0933 grams of biofilms were produced.

c) Biofilms made from commercial starch (perunajauho)

13.5 grams of commercial potato starch (perunajauho) was mixed with 135 mL of distilled water in a beaker and then put to heat. In addition, 10.8 mL glycerol and 16.2 mL vinegar were added to the mixture and the mixture was heated for 20 minutes at 100°C. After that, the mixture was then put into petri dishes symmetrically for 72 hours at room temperature. 8.7273 grams and 3.2379 grams of biofilms were extracted.

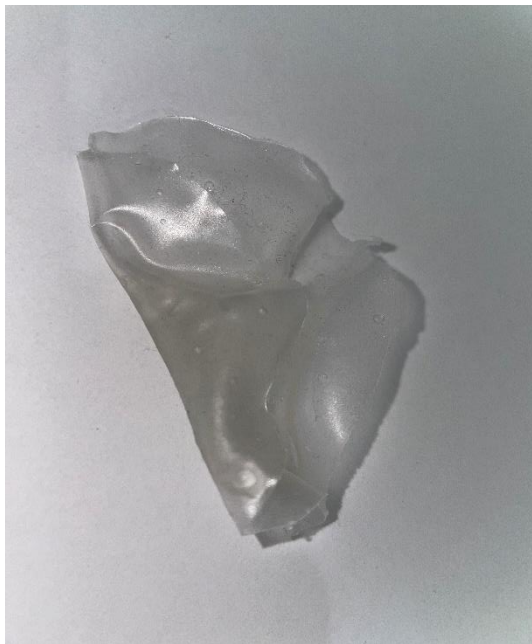


Figure 28: biofilm sample C (3.2379g)



Figure 27: biofilm sample 3 (8.7273g)



Figure 29: making bio-films

3.4.3 Biodegradation process

After making the biofilms, all the biofilms were buried inside soil in two different soil conditions. Three different biofilms made from lab-made, mixed (lab-made+commercial) and commercial starch, were buried in normal soil condition in a park near my apartment in Espoo, Finland. The environmental conditions such as temperature, condition of the soil (dry or wet) was noted down. Figure 30 is the park where three films were buried. 30 cm of hole was made. and the films were labelled and buried with the distance of 10 cm from each other. The films were buried in 19th of July until 19th of August 2022. Three films sample i.e., films made from lab-made starch, lab-made+commercial starch and commercial starch were buried each in normal environment in a park and in a composter on the balcony of an apartment. Each sample were given unique names to make it easier to locate and to give precise measurement. The weather conditions at the time when the samples were kept in the burry was hot and dry which is why the composter was continuously watered.



Figure 30: the park where films were buried

Figure 31 shows the location of the park where the films were buried.

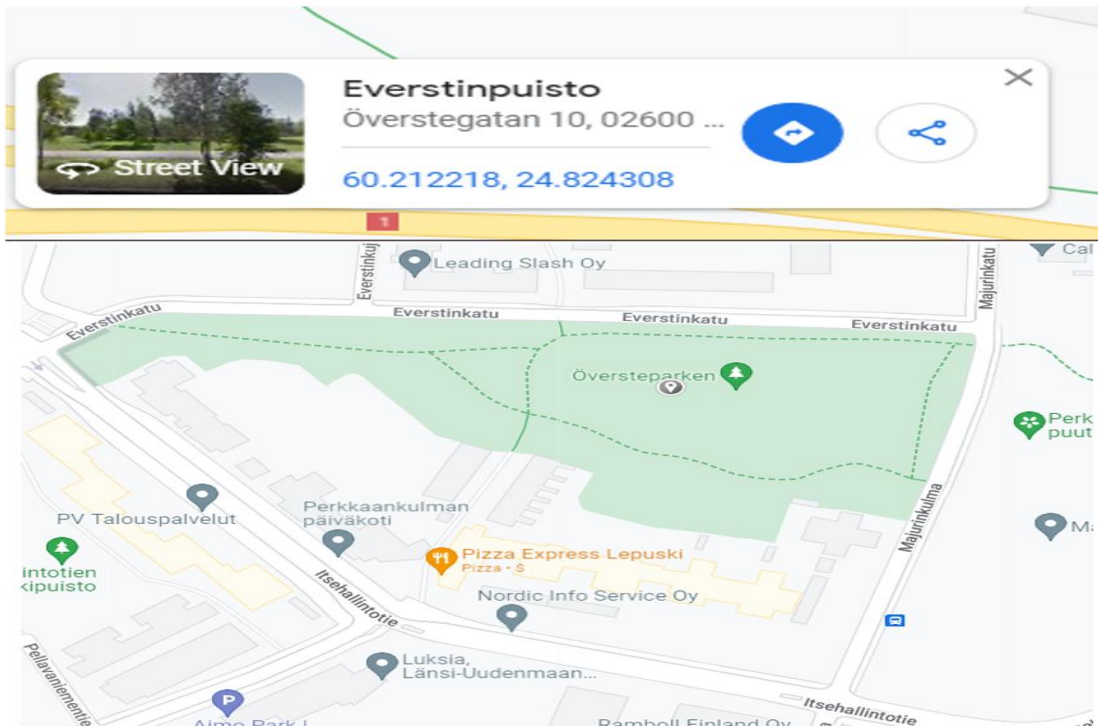


Figure 31: location of the park where films were buried in Espoo, Finland.

On the other hand, other three biofilms were buried in a commercially bought composter (Bokashi compost activator with microorganisms). The composter was bought from Clas Ohlson. The biodegradation was done in commercial composter as an indoor soil burial degradation following the article written by (J. Prakash Maran, 2014). Three different films were buried inside the bio-composter with films labelled each with their respective weights. The films were put for 30 days with continuous monitoring and watering it regularly. The composter was kept in constant room temperature: 22-30°C. The films were buried in two soil conditions to compare the degradations in two conditions.

Tiny worms were seen growing in the composter during the time of biodegradation in Figure 32 and 33.



Figure 32: worms growing in indoor biocomposter



Figure 33: indoor biocomposter

4 RESULTS

There were many impurities in the starch that was extracted from the potato peels in the laboratory which is why the films made were brownish in color. On the other hand, after putting the films to dry in petri dishes, it was difficult to take some of the films out of the petri dishes which resulted in 2-3 pieces of a single film.

In addition, the biodegradability tests were done in normal environment and commercial composter. The films were buried for a month. Three films sample i.e., films made from lab-made starch, lab-made+commercial starch and commercial starch were buried each in normal environment in a park and in a composter on the balcony of an apartment. Each sample were given unique names to make it easier to locate.

Figures 34, 35, 36, 37 and 38 are the images that show before burying and after the films were taken out from the composter and data that were measured and found during the project. The films had color changed and was brittle after 30 days of degradation.

4.1 Biodegradation in Bokashi compost activator with microorganisms



Figure 35: sample A before burying



Figure 34: Sample A after 30 days of burying in composter

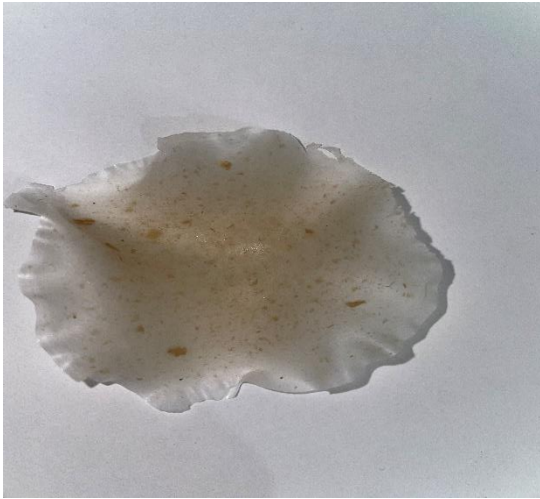


Figure 37: Sample B before burying



Figure 36: Sample B after burying in composter

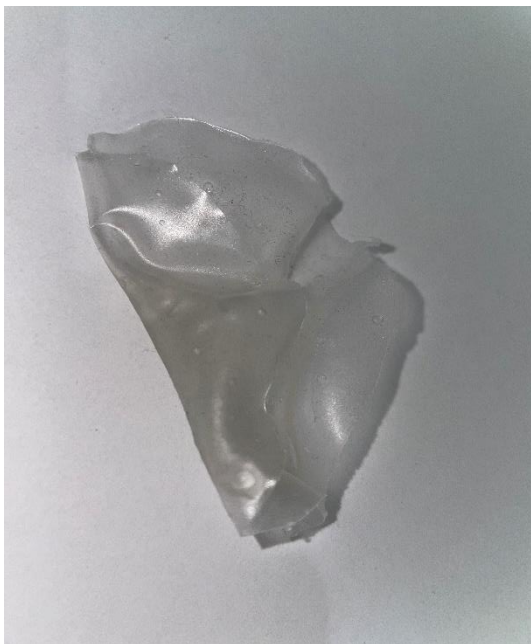


Figure 39: Sample C before burying



Figure 38: Sample C after burying in composter

The table below shows the weight of the films before burying and weight after 30 days of degradation process in the composter.

Table 2: data of samples buried in composter

Samples	Type	Room temperature (°C)	Weight before burying (g)	Weight after 30 days of burying (g)
A	Film made from lab-made starch	22-30°C	1.338	0.0577
B	Film made from mixed starch	22-30°C	11.7985	1.8364
C	Film made from commercial starch	22-30°C	3.2379	0.9848

Using the weight loss formula i.e., Weight loss (WL) = $\frac{\text{Initial weight (Wi)} - \text{final wight (Wf)}}{\text{Initial weight (Wi)}} \times 100\%$ (Arikan & Bilgen, 2019), the weight loss for each samples were found to be;

Weight loss for sample A = 95.68%

Weight loss for sample B = 84.43%

Weight loss for sample C = 69.6%

4.2 Biodegradation in normal soil condition in a park

Figures 38, 39, 40 and 41 below shows the films before burying and after burying in a normal soil conditions.

However, samples 1 and 2 were completely degraded after burying in normal soil conditions after 30 days as the labels were located but samples were not which is why there are no pictures of it.



Figure 40: sample 1 before burying



Figure 43: sample 2 before burying



Figure 42: Sample 3 before burying

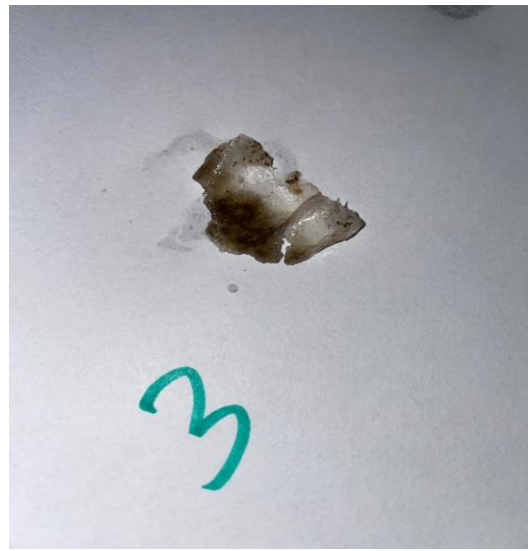


Figure 41: Sample 3 after burying

Table 3: data of samples buried in normal soil environment

The table below shows the weight of the films before burying and weight after 30 days of degradation process in the normal environment;

Samples	Type	Environmental condition	Weight before burying (g)	Weight after 30 days of burying (g)
1	Film made from lab-made starch	20°C, sunny and moist soil after rain	2.7737	0
2	Film made from mixed starch	20°C, sunny and moist soil after rain	3.0933	0
3	Film made from commercial starch	20°C, sunny and moist soil after rain	8.7273	0.0915

Using the weight loss formula i.e., $Weight\ loss\ (WL) = \frac{Initial\ weight\ (W_i) - final\ weight\ (W_f)}{Initial\ weight\ (W_i)} \times 100\%$ (Arikan & Bilgen, 2019), the weight loss for each samples were found to be;

Weight loss for sample 1 = 100%

Weight loss for sample 2 = 100%

Weight loss for sample 3 = 99%

The graph (Figure 42) below shows the weight loss data of the films that were buried in composter and normal environment in percentage.

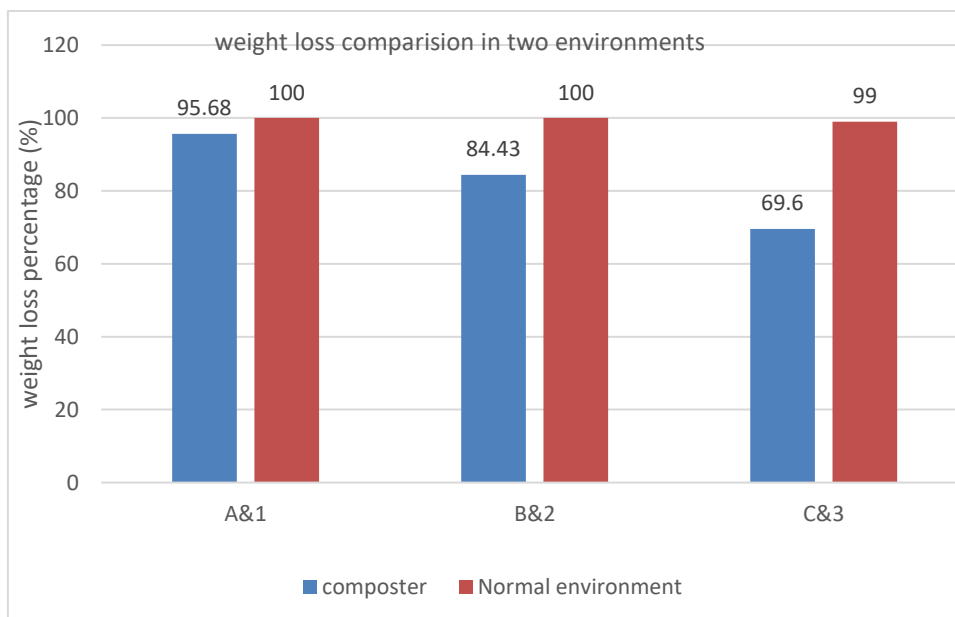


Figure 44: weight loss percentage of films

4.3 FTIR analysis

Multiple analyses were done. The original and biodegraded films were analyzed to find out the functional group and basic discussion in the samples. For example, in Figure 45, the blue color in the graph shows the FTIR result of the original sample that was made from the lab-made starch while the red color shows the result of the sample that was biodegraded in composter. The absorbance peak for both samples lies between 3400 cm^{-1} to 3200 cm^{-1} which explains that OH group is present in the samples. However, the amount of IR radiation absorbed by the biodegraded sample was low as compared to the original one. The nature of the fluctuation in the original and biodegraded samples are very similar to that of sample A. All the other FTIR analysis results are shown below in appendix. On the other hand, library comparison against the samples were also done which can be found in appendix below.

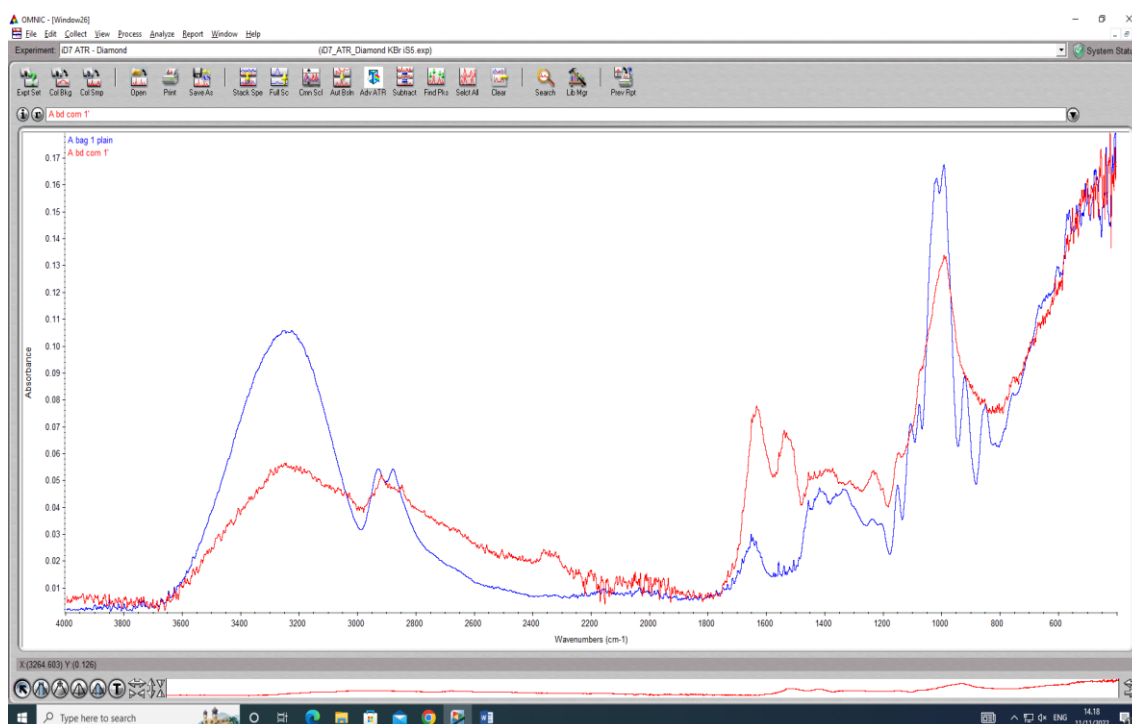


Figure 45: sample A original vs biodegraded

5 DISCUSSIONS AND CONCLUSIONS

The main objective of this thesis was to test the biodegradability of laboratory made bioplastic films. The project is completed with good results. However, after some discussions with the supervisor, potato peel starch as a main source to produce biofilms, replaced the initially thought source i.e., starch from the fruit peels. In addition, the industrial composter facility for the biodegradability test was difficult to find which is why homemade mobile composter was used for the biodegradation process and the results were good. On the other hand, FTIR analysis is also done to know the difference in chemical composition of the films before and after the biodegradability test which was not initially in the objective. In this project, six different samples of biofilms were produced from potato starch. The starches were heated with vinegar, glycerol and water and the films were made. The films were extracted in the laboratory from three different starch types. Two samples were made from each lab-made, mixed and commercial starch. Those samples were given unique identity i.e., sample A,B,C and sample 1,2,3. The samples, A,B,C were buried inside the composter while the samples 1,2,3 were buried inside the soil in normal environmental conditions. The two samples i.e., sample 1 and 2 were completely degraded in normal environmental conditions. While a tiny piece of sample 3 was found. On the other hand, the samples A, B and C that were buried in indoor composter showed promising degradation as well. However, I believe that if the samples were buried in an official biocomposter that contained many microorganisms, the films would have degraded completely. If we compare the degradation of samples in two environments, the samples that were buried in normal environment showed promising result compared to the ones that were buried in composter indoor. The reason behind it was probably because of the humidity as the indoor burying process could not match the standard of bio composting as the standard bio composter was not available nearby. However, the weight loss report was promising.

Another interesting result was found after the samples were taken out after 30 days. The weight loss of the samples that were made from lab-made starch was more than that made of commercial and mixed starch. 95.68 %, 84.43% and 69.6% of films made from lab-made starch, mixed starch and commercial starch respectively were degraded in composter after 30 days. On the other hand, the films made from lad-made starch and mixed

starch were completely degraded in normal environment. However, 99% of film made from commercial starch was degraded in normal environment.

While making the films in the lab, the timing and temperature should be noted carefully to get symmetrical viscous liquid which is later put in the petri dishes. In this way, one can get symmetrical biofilms. On the other hand, if one could find the industrial composting facility, better results could be founded.

To recapitulate, the usage of biodegradable plastics is suitable for the planet. It helps in sustainability, circular economy, and less pollution.

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7 APPENDIX

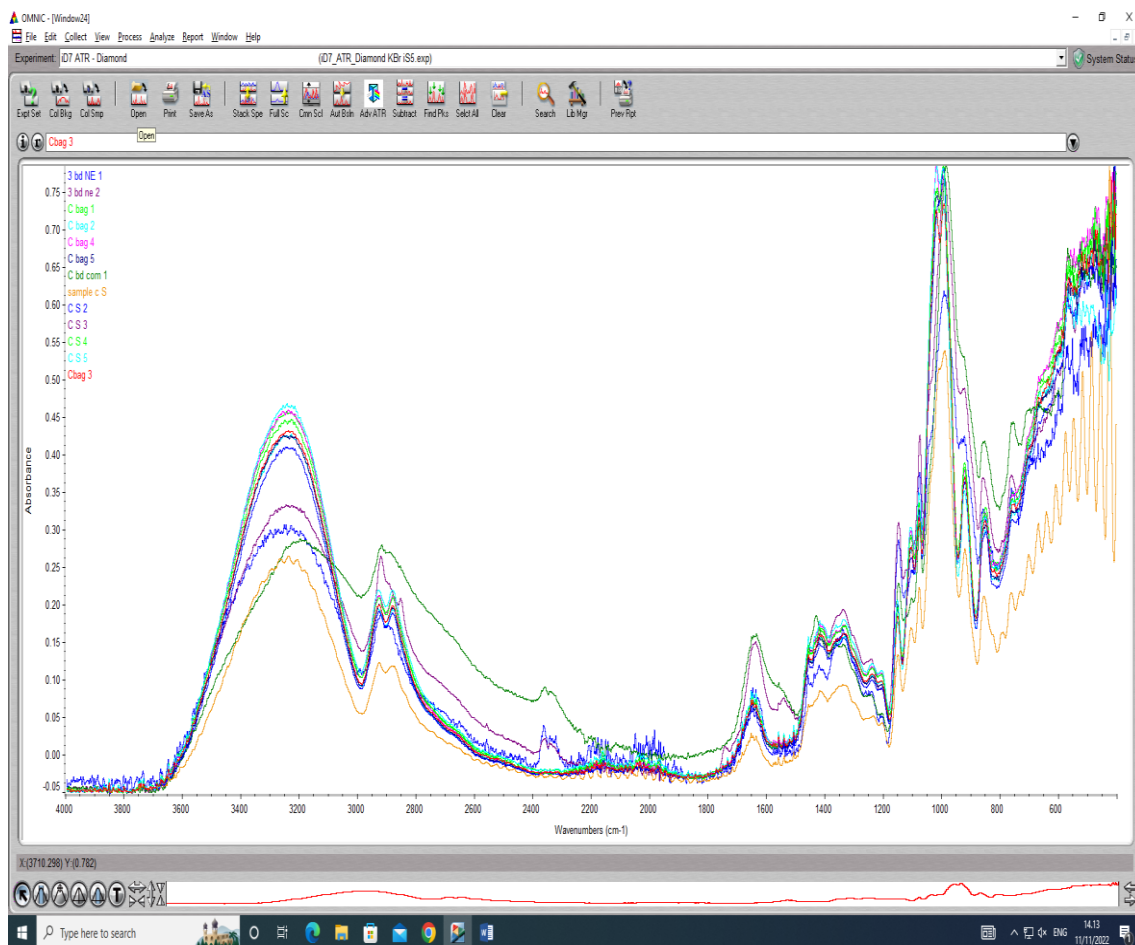


Figure 46: sample 3 original vs biodegraded in normal environment

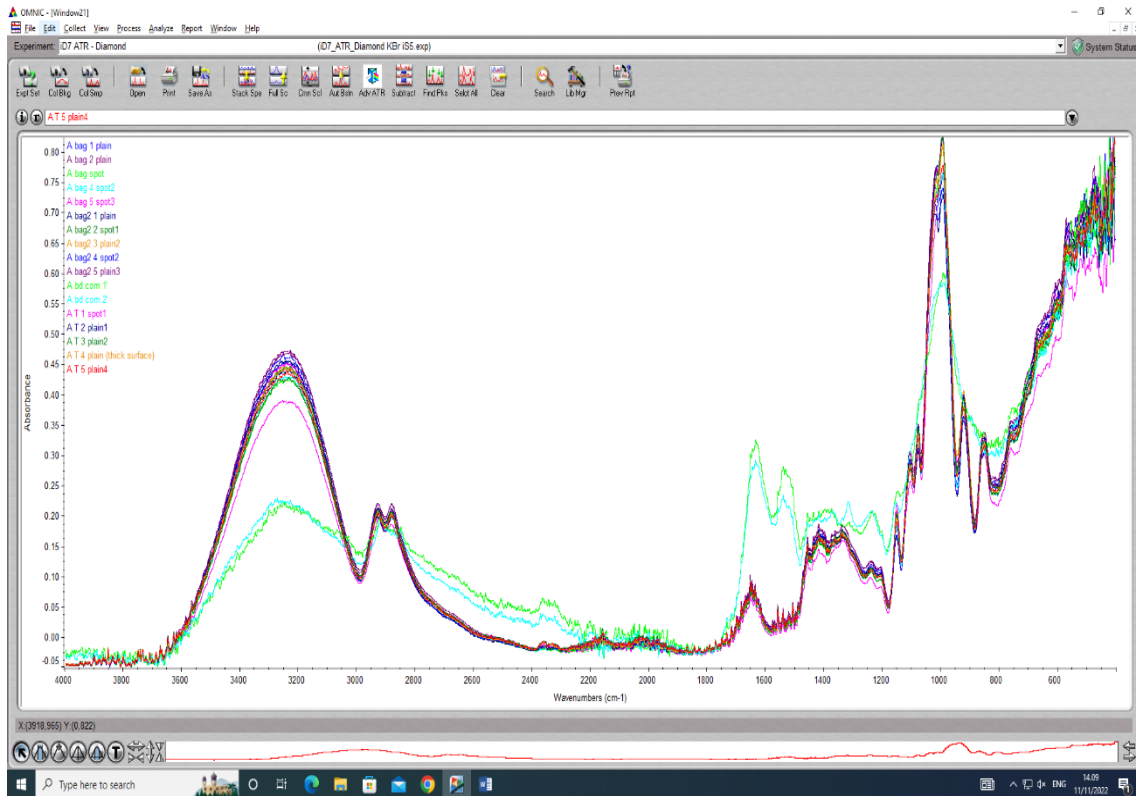


Figure 47: sample A original vs biodegraded in composter

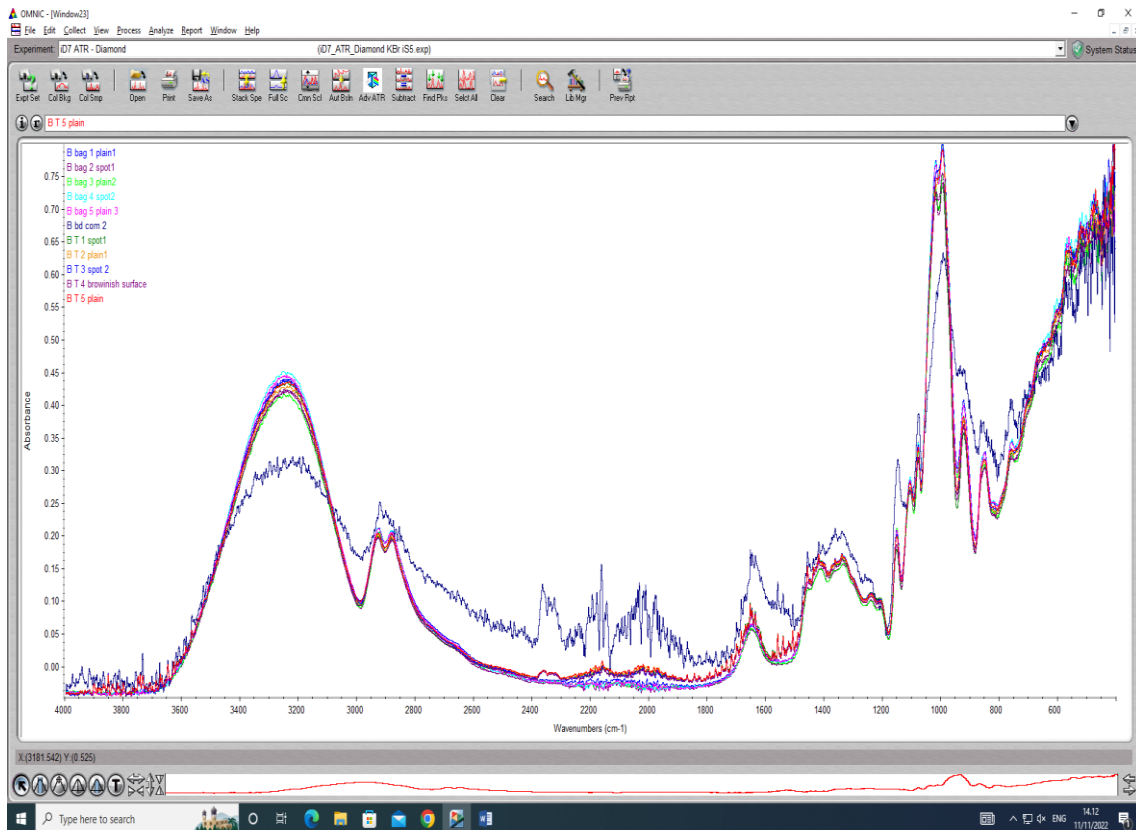


Figure 48: sample B original vs biodegraded in composter

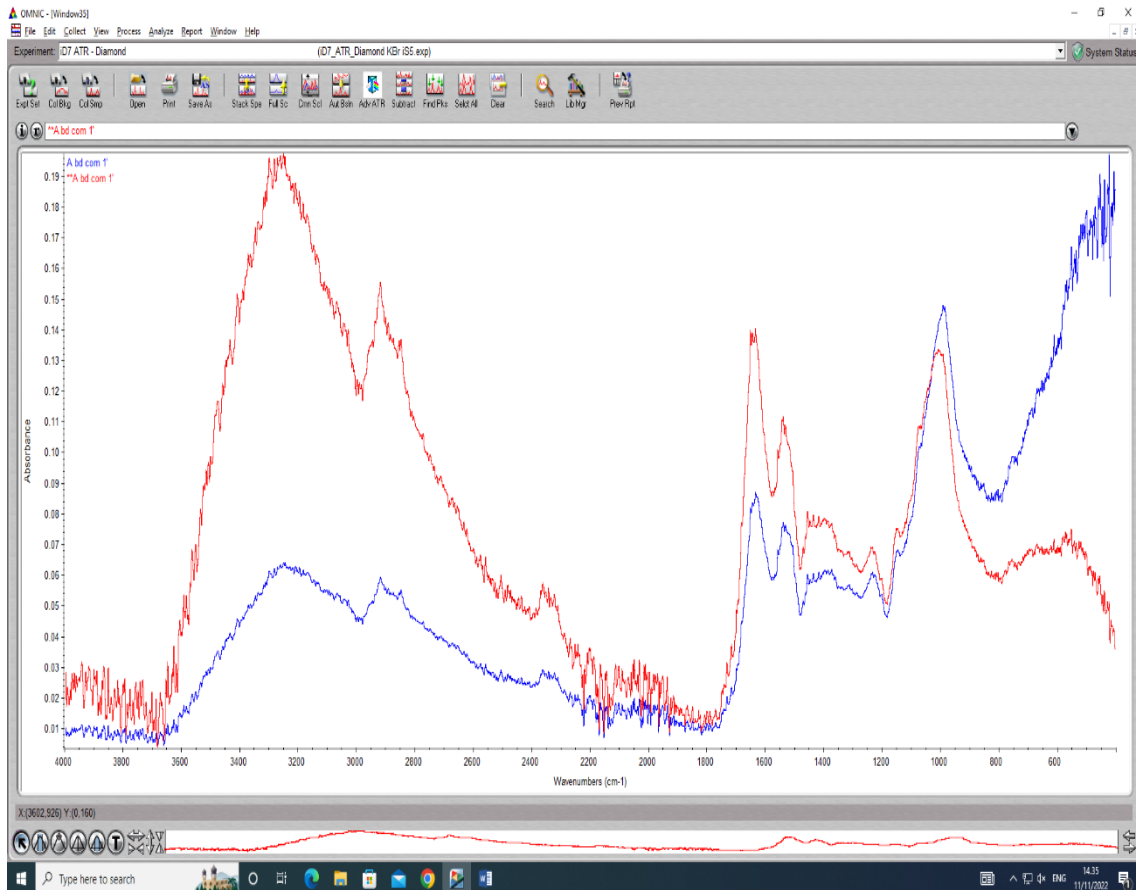


Figure 49: Library comparison of sample A biodegraded in compost

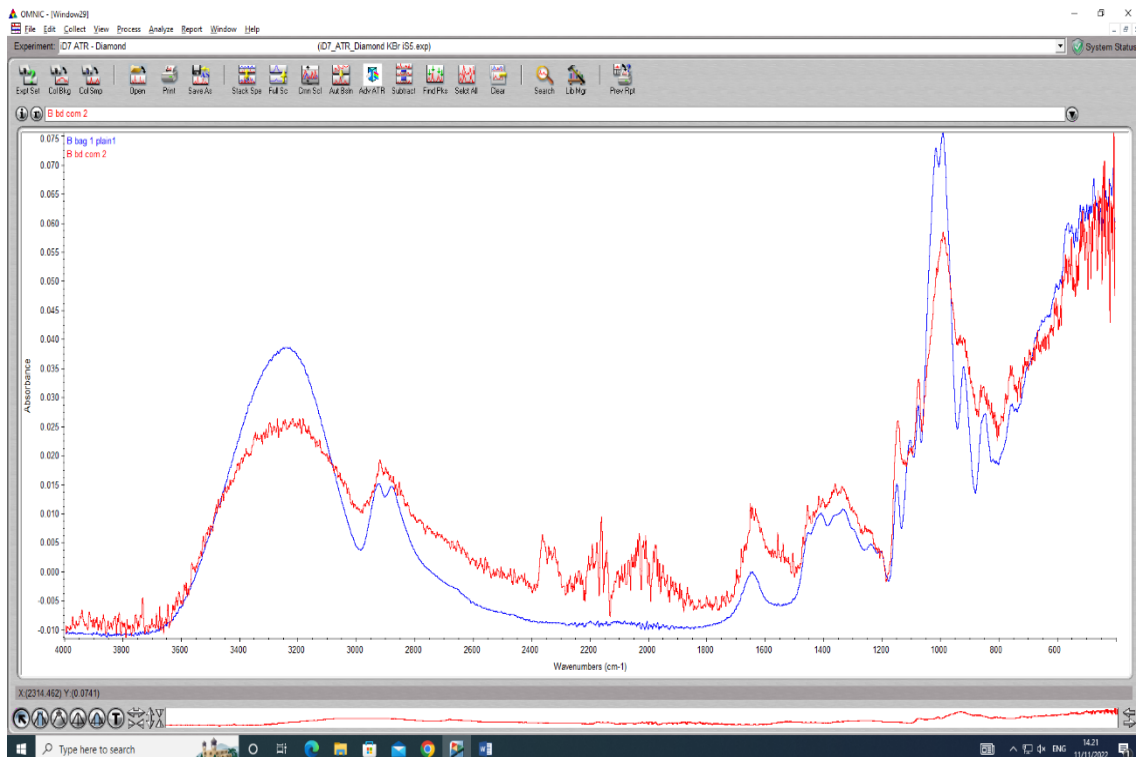


Figure 50: Sample made from mixed starch (original and biodegraded in compost)

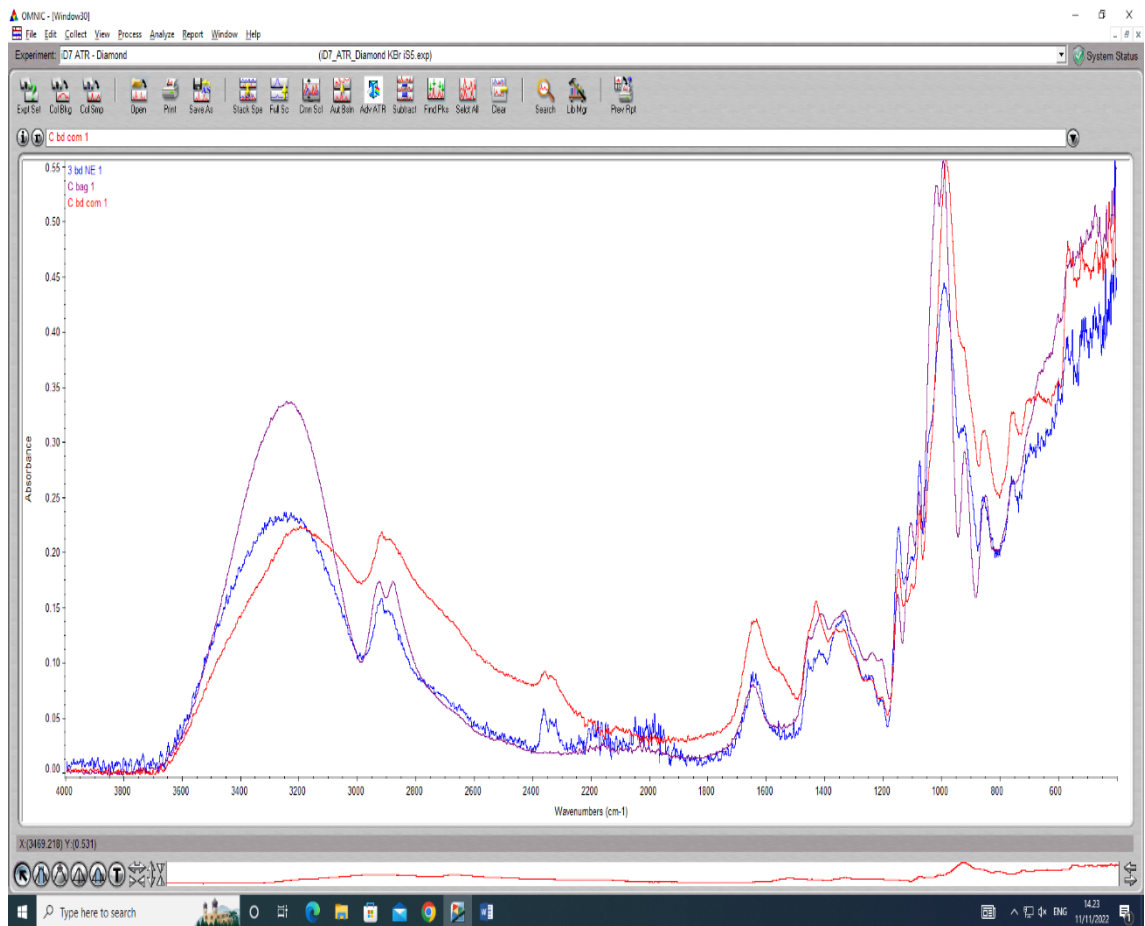


Figure 51: sample C: original, biodegraded in composter and biodegraded in normal environment.