TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

DETERMINATION OF THE SUITABILITY OF COMPOST AND CELLULOSE AS A REFERENCE MATERIAL FOR TESTING OF BIODEGRADABILITY OF BIOPLASTICS

KOMPOSTI JA TSELLULOOSI KASUTAMINE VÕRDLUSMATERJALINA BIOPLASTIDE LAGUNDAMISEL

MASTER THESIS

Student:	Hewa Karanappulige Udesh Sanjeewa Wickramarathne
Student code:	194378 EABM
Supervisor:	Dr. Viktoria Voronova (Senior lecturer)
Co - Supervisor:	Pavlo Lyshtva (PhD student)

Tallinn 2021

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

“.......” .... 20 ….

Author: ....
/signature /

Thesis is in accordance with terms and requirements

“.......” .... 20….

Supervisor: ….........................
/signature/

Accepted for defence

“.......” .... 20….

Chairman of theses defence commission: ....
/name and signature/

Non-exclusive Licence for Publication and Reproduction of GraduationTthesis[1]

I, Hewa Karanappulige Udesh Sanjeewa Wickramarathne (date of birth: 16/02/1992) hereby

1. grant Tallinn University of Technology (TalTech) a non-exclusive license for my thesis Determination of the suitability of compost and cellulose as a reference material for testing of biodegradability of bioplastics, supervised by Dr. Viktoria Voronova.

1.1 reproduced for the purposes of preservation and electronic publication, incl. to be entered in the digital collection of TalTech library until expiry of the term of copyright;

1.2 published via the web of TalTech, incl. to be entered in the digital collection of TalTech library until expiry of the term of copyright.

1.3 I am aware that the author also retains the rights specified in clause 1 of this license.

1. I confirm that granting the non-exclusive license does not infringe third persons' intellectual property rights, the rights arising from the Personal Data Protection Act or rights arising from other legislation.

---

[1] *Non-exclusive Licence for Publication and Reproduction of Graduation Thesis is not valid during the validity period of restriction on access, except the university`s right to reproduce the thesis only for preservation purposes.*

______________ (*signature*)

______________ (*date*)

Department of Civil Engineering and Architecture

THESIS TASK

Student: Hewa Karanappulige Udesh Sanjeewa Wickramarathne 194378EABM

Study programme: EABM03/18 - Environmental Engineering and Management
Supervisor: Senior Lecturer, TalTech. Dr. Viktoria Voronova, +3726202506,
viktoria.voronova@taltech.ee

Co-supervisor: PhD student, TalTech. Pavlo Lyshtva, +37258055196,
pavlo.lyshtva@taltech.ee

Thesis topic:

(in English) Determination of the suitability of compost and cellulose as a reference material for testing of biodegradability of bioplastics.

(in Estonian) Komposti ja tselluloosi kasutamine võrdlusmaterjalina bioplastide lagundamisel

Thesis main objectives:

1. Literature review
2. Development of aerobic and anaerobic composting system with controlled conditions
2. Analysis of aerobic and anaerobic composability of compost sample and cellulose.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Choosing thesis topic	1st February 2021
2.	Literature review	31st March 2021
3.	Composting system development	31st March 2021
4.	Results analysing	30th April 2021
5.	Thesis finalization	10th May 2021

Language: English **Deadline for submission of thesis:** "......." 2021

Student: Hewa Karanappulige Udesh Sanjeewa Wickramarathne

.... "......." 2021
/signature/

Supervisor: Dr. Viktoria Voronova ……………………. “.......” 2021

/signature/

Co - Supervisor: Pavlo Lyshtva …...................... “.......” 2021

/signature/

Head of study programme: Prof. Karin Pachel

……….............“.......” 2021

/signature/

Terms of thesis closed defence and/or restricted access conditions to be formulated on the reverse side

Table of Contents

PREFACE

Conventional plastic is one of the biggest environmental pollutants in the world which impact the human health, animal lives, land, and sea pollution. Most of the modern research are driving towards to find more sustainable and environmentally friendly polymer materials to fight against with conventional plastics. BIO-PLASTICS EUROPE project is also one of the biggest initiatives which is finding sustainable solutions for bio-based plastics on land and sea. This thesis was influenced and resourced to write by one of the areas of this project which is innovative product design.

Testing the properties of newly developed materials in laboratory scale, before introducing it in the market is quite important to find the problems in beforehand. This thesis is based on the experiments conducted to find the ultimate aerobic and anaerobic biodegradability of bioplastic material under the controlled conditions. This report discusses the current situation in the world of conventional plastics and bioplastics, the method used to calculate the biodegradability and the results obtained from the laboratory testing. The reader can have a better idea of how important the reference materials like compost and cellulose is to compare the successfulness of the modified bioplastic material in the point of disposal to the environment.

This experimental data of newly developed polymer material can use to change the plastic industry for the better environmentally friendly industry in near future. Successfully developed bioplastics will replace the conventional plastics and give the similar experience to the consumer without any difficulty.

As the author of this thesis, there are several people who should share the credit of the successfully completing this experiment and the report specially Dr. Viktoria Voronova the supervisor of this master thesis, Mr. Pavlo Lyshtva the co-supervisor of this thesis, and Researcher at TalTech Dr. Argo Kuusik.

BIOPLASTIC, CONVENTIONAL PLASTIC, BIODEGRADABILITY, AEROBIC AND ANEROBIC, MASTER THESIS

LIST OF ABBREVIATIONS AND SYMBOLS

PET	Polyethylene Terephthalate
HDPE	High density Polyethylene
PVC	Polyvinyl Chloride
LDPE	low density Polyethylene
PP	Polypropylene
PS/EPS	Polystyrene
PLA	Polylactic acid
PHA	Polyhydroxyalkanoates
TPS	Thermoplastic styrenicelastomers
PBS	Polybutylene succinate
PBAT	Polybutylene adipate terephthalate
PCL	Polycaprolactone
PE	Polyethylene
PTT	Polytrimethylene terephthalate
TDS	Total Dry Solids
TVS	Total Volatile Solids

1 INTRODUCTION

Since the late 19th century plastic became the most common packaging material all around the world due to its easy use and the portability to the consumer. Until today thousand tons of plastic products are added to the market to fulfil the customer demand. With the technology evaluation several types of plastics were manufactured for different types of purposes. But none of these plastic types were healthy to the environment [1]. Day by day used plastics are accumulating in the soil and sea all around the world [2]. Sometimes due to the incineration of these plastic materials, tons of carbon dioxide are emitted to the atmosphere.

Throughout the life cycle of plastic products, it has environmental impacts which will directly and indirectly affecting the humans, fauna, and flora. Plastics contains hazardous compounds in their long molecular chains and since production to the final disposal or incineration, these chemicals are contaminating the soil and the sea [1]. Microplastics are one of the uprising environmental impact to the world.

Scientists, authorities, and responsible citizens were not understood the consequences of ordinary plastics until the magnitude of impacts were become tremendous. Even today there are large solid waste mountains contains major amount of plastic in some countries without any proper treatment [3]. Major portion of total solid waste in the world is taken by the plastic.

The first innovative solution for the conventional plastics problems was developing bioplastics. These bioplastics are divided into two main types by the material it produced and the biodegradability of it [4]. The most environmentally friendly bioplastics are the bio-based biodegradable bioplastics [5]. At present bioplastics are taking over 1% of plastic industry and it is a rapidly growing industry [6]. But bioplastics also have drawbacks which need to identify and improve for the further development. Main problems are the current high cost and complex process of producing bioplastics. Also compared to current conventional plastics, bioplastic have poor mechanical properties which is limiting the commercial applications.

Therefore, the properties of these bioplastics are quite important to study and analyse to identify the applications, further development, and problems before releasing into the market. One of the most important parameters needs to evaluate in bioplastic is the biodegradability in soil medium.

This study is focused on biodegradability of bioplastics in the aerobic and anaerobic environments. To analyse the degradation of new materials, there should be a reference material to compare the results. The objective of this thesis is to evaluate the suitability of compost and cellulose as a reference material for testing of the biodegradability of new bioplastics under controlled aerobic and anaerobic conditions.

2 LITERATURE REVIEW

2.1 Overview of conventional plastic

Since the beginning of the 19th century plastic became one of the most important raw material to most of the industries [2]. Synthetic polymers were becoming quite popular drastically due to its exceptional physical and chemical properties. These plastic materials have long chains of carbon atoms and based on their arrangement and the other chemical compounds bounded to the main chain, scientists have discovered several types of plastics for different types of usages. Conventional plastic is manufacturing from the petrochemicals and the other petroleum products coming from the fossil fuel industry [2].

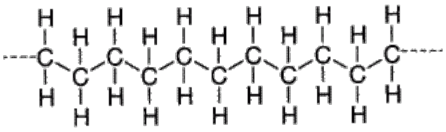


Figure 1: Basic polymer chain [7]

Based on the covalent bonds in between carbon atoms, the structure of their arrangement and the other atoms and molecules bounds to the main carbon chain, there are several types of plastics. For instance, most common plastic types in the market are Polyethylene Terephthalate (PET), High density Polyethylene (HDPE), Polyvinyl Chloride (PVC), low density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS/EPS) [8] [9].

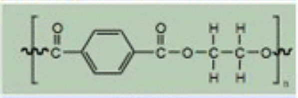
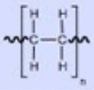
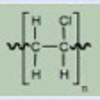
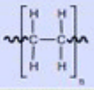
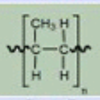
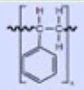
Polymer	**Polymer Structure**
Polyethylene Terephthalate	
High-density Polyethylene	
Polyvinyl Chloride	
Low-Density Polyethylene	
Polypropylene	
Polystyrene	

Figure 2: Polymer Structures [10]

Based on the properties of the above-mentioned common types of plastics, these plastics are using for the industrial applications and consumer applications as following table.

Table 1: Applications of different types of plastic [9]

Type of Plastic	**Application**
PET	Beverage bottles Textile applications
HDPE	High density liquid bottles (e.g., Oil, milk, etc.) Construction pipes
PVC	Construction materials (window frames, plumbing pipes)
LDPE	Grocery bags
PP	Food containers, PP cups, bottle caps
PS/EPS	Construction materials (as an insulation material) Food containers, Cups

2.1.1 Advantages of conventional plastic

The most important factor to become the plastic more popular among the consumers is its light weight, versatile and durability. Compared to most of the other related products like glass or metal, plastic has low mass per unit volume [8]. This property improved the portability of the product or the product inside the plastic container. With regards to the paper or cardboard competitive products, plastic has more durability and a higher number of cycles of reuse. In the same time plastic is water resistant and the products inside the plastic containers are safer than paper and cardboard containers [8] [9].

Plastic materials become more popular in the construction industry specially in the water and sewage systems because polymer materials do not react with the corrosive substance in those liquid flows. One of the major impacts of metal pipes is its frequent maintenance due to the pipe corrosion [8]. This property of plastics quickly replaces the metal from construction industry all over the world fast. More importantly the liquid inside the plastic pipelines has quite low possibility to leak and contaminate the ground, water, and soil. This scenario is more important in sewage line systems and the vies versa of this applies to the purified drinking water lines. [8].

Throughout the time plastic materials made people lives more easier and safer in different areas. People get used to use plastic products all over their lifestyle. Since the beginning manufacturers manage to produce plastic products for quite low price too.

Therefore, people did not have the intention or the interest to find other alternatives to compete with plastics [2].

2.1.2 Disadvantages of conventional plastic

Even though plastics have more durability and lots of other useful properties, it has slow degradation when it added to the environment. For instance, a plastic bottle will stay in the marine system for 58 years after it disposed [11]. In the same time people do not manage to reuse or recycle the plastics. One of the most important reason for that is plastics came with a quite cheap price to the marker. Other than reusing or recycling it, people bought new products and due to that tons of plastic waste accumulate especially on the land and sea. Other than that rapid urbanisation and higher population density, inadequate waste treatment techniques and facilities used by each country, and industrial disposal and loss during production and transport are directly corelating with the pollution from the plastic [11] [12].

Currently world is producing more than 360 million metric tons of plastic per year [13]. From the plastics manufactured from 1950 to 2015, only 9% of it was recycled [11]. The rest of the plastic waste ended in environment impacting the flora and fauna as well as human health.

The plastic ends up in the soil or sea will cause major health impacts on terrestrial and aquatic animals [14]. Physical harms can mainly occur by entanglements or ingestion to the animals. Most commonly the plastic entanglements can see on the sea turtles and birds. Most of the large mammals and birds are dying due to plastic pieces stuck in their digestion system with food. Most of the chemical hazards to the environment is occurring due to the additives which are using for the plastic manufacturing. Also, microplastic and nano plastic have a huge responsibility on these impacts. These chemicals will cause development issues, reproductive effects, and skin diseases on animals [14]. The impacts of chemical hazards will affect humans as well from the food chain. Transferring accumulated chemicals specially in sea animals by consuming as food, humans also in danger with plastic pollution [14]. The impacts on the plant life are quite similar to animals. Plastic accumulate in the soil will disturb the nutrients and water to absorb from the roots of the trees and it will slow down the plant's growth. Human food sources are getting weaker and low quality, tourism attractions will fade, and health impacts are the most common and catastrophic consequences that man have to find solutions in near future. Ultimately all these environmental impacts are affecting the development of next generation directly or indirectly.

2.1.3 Legislative control for the conventional plastic

Most of the governmental and central authorities in developed and developing countries have seen the environmental impacts from conventional plastics few decades back and enforce number of restrictions and regulations to reduce the plastic pollution.

One of the most common issue for all the countries in the world are single use plastic bags. These plastic bags have accumulated day by day and governments and regulating authorities are struggling with recycling or disposing those properly [15]. However, the most effective and reliable way of solving this problem is to minimise the plastic waste generation from the starting point. For that most of the countries have to enforce restrictions on producing and importing single use plastic bags [15]. For instance, the southern African development community which created by 16 countries in African continent have enforced national bans and partially bans for import, manufacture or use plastic bags thick less than 24 microns. For the institutes or individuals who break or disobey this restriction will sentence with 3 years jail time and up to 620 American dollars fine [15].

Another problem that the governments have to face nowadays is illegal migration of plastics. This is occurred mainly from developed countries to the developing countries. India is becoming one of the biggest countries which face this problem recently. Some privet companies illegally import plastic waste from the industrialized countries and dispose in unsanitary landfills. India and other south and middle Asian countries are now developing their governmental policies on preventing this problem [16].

Taiwan is an east Asian country which successfully enforced recycling plastic policy in 1997. More than plastic ban, taxes, penalties and fines they believe the behavioural change from the education is one of the strongest solutions for the pollution from plastic [17].

Almost 26 million tons of plastic waste is producing in Europe per year [18]. But the EU is driving their waste management policies strongly to minimise impact on environment. In 2015 the directive 2015/720/EU which is describing the "reducing the consumption of lightweight plastic carrier bags" manage to enforce their member states to monitor the usage of plastic bags and apply economical solutions against the pollution from it [19]. "The European strategy for plastic in a circular economy" was approved by the European commission (EC) in 2018 to save the environment and people from the environmental pollution [20].

Going beyond from the major plastic pollutants, American federal law has voted for the “Microbeads free water act” to maintain the quality of water preserving from micro and nano particles. This act has enforced on cosmetics products which have intentionally added non-biodegradable plastic microbeads [19].

2.1.4 Recycling of conventional plastic

Governments, regulating bodies and the private sector investing millions of dollars each year to develop and maintain plastic waste management centres.

There are two main approaches of plastic recycling in circular economy. First one is open loop recycling which means the recycled plastic use for applications which are different from the original product. Most commonly the recycled plastic is use for low quality products then the original use [21]. The second one, close loop recycling approach is keeping the material in the same product cycle after recycling. This is a more circular option than the open loop recycling because this reduces the virgin material usage and keep material at higher value chain [21].

The major bottleneck of close loop recycling is the additives that are using in the manufacturing processes. These chemicals or particles are mainly using as functional additives, colourants, fillers or reinforcements [21]. Based on the composition or the chemical bonds, there are 4 main recycling technologies in the industry [22].

1. Primary recycling – mechanical and/or chemical recycling (mainly in close loop recycling)
2. Secondary recycling – mechanical and/or chemical recycling (mainly in open loop recycling)
3. Tertiary recycling – feedstock, pyrolysis, depolymerisation, hydrolysis (on bio plastics)
4. Quarterly recycling – energy recovery or incineration [21] [23].

Even though the recycling technologies are available and develop continuously, the recycling rate of the plastic in the world at the moment is only 30% [21]. Major portion of plastic waste producing in the world in each year goes into the landfills or sea.

Main reasons for not succeeding the plastic recycling are the cost of recycling and the technical aspects of industries. At the same time there are safety issues with materials which are not supposed to be in the plastic such as glass, needles or chemical residue. Environmental impacts also high in recycling process because due to emissions of harmful substances and release of leachate into the soil [24].

Because of these reasons scientists encouraged to invent modified materials which have low environmental impact than conventional plastics. As a result, bioplastics were invented, and they have the potential to replace the conventional plastic applications and give sustainable solutions compared to the ordinary plastics.

2.2 Overview of Bioplastics

Bioplastics are also a polymer family, in general referred to both bio-based plastics and biodegradable plastics. Most of the current bioplastics are non-biodegradable bio-based plastics [1] [5]. Around 85% of plastic applications in the world at the moment can be replaced by the bio plastics [25]

Bio-based biodegradable plastics have long carbon chains in their molecular state which can easily breakdown into the smaller components by biological reactions like bacteria, fungi, algae, or other microorganisms [26] [27]. Fossil fuel based biodegradable plastics have additives and reactive particles in their polymer structure which can accelerate the degradation in the presence of sunlight and oxygen [27]. The important of moving into bio-based plastics is it is a positive movement toward the circular economy [25].

Bio based plastics use natural polymers from the biomass like potato starch, corn starch, rice oil, sugarcane, vegetable fat, milk etc. for the polymerisation [1]. The bio based plastic production process include pre-treatment of degradable content, hydrolysis, fermentation, and several steps of organic reactions [1].

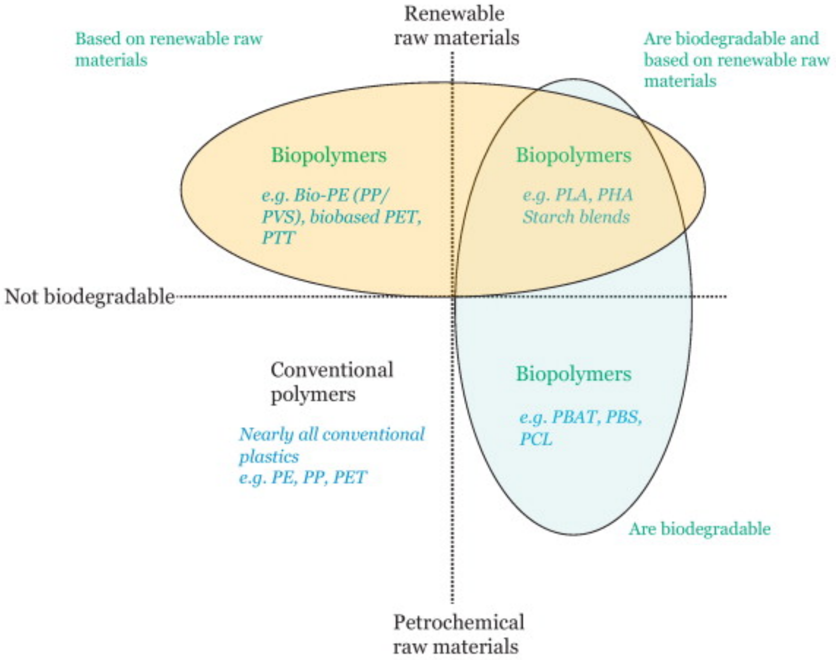


Figure 3: Types of bioplastics [4]

2.2.1 Types of bioplastics

Bioplastics can be classified into 3 main groups (Figure 3). Most environmentally friendly category of bioplastic type is bio based biodegradable polymers and the other categories are bio based non-biodegradable plastics and fossil fuel based biodegradable polymers.

Most common bio-based biodegradable plastics in the market are Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), Thermoplastic styrenic elastomers (TPS) and Polybutylene succinate (PBS) [1] [28].

Bio-based non-biodegradable plastics are categorised as following:

1. Bio based thermoplastics – bio-PP, bio-PET, bio-Polyethylene (PE)
2. Polymers like bio- Polytrimethylene terephthalate (PTT), bio-nylon
3. Thermosets – bio polyurethanes, unsaturated polyesters, and epoxies [28]

Common fossil fuel based biodegradable plastics in the consumer market are Polybutylene adipate terephthalate (PBAT) and Polycaprolactone (PCL) [28].

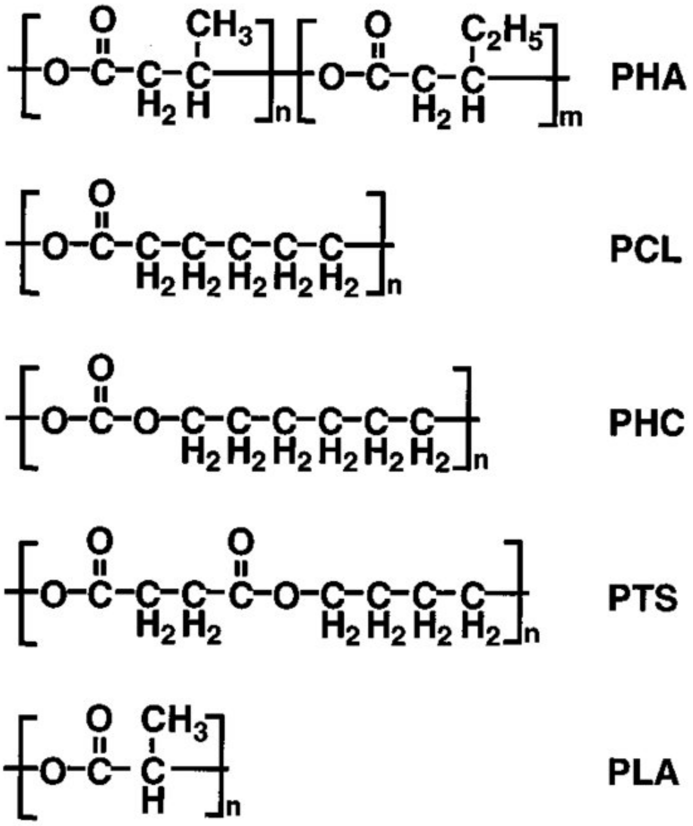


Figure 4: structures of bioplastic [29]

2.2.2 Market analysis of bioplastics

In the current market amount of plastics are around 368 million tons per year, and only around 1% is taken by the bioplastics [6] [30]. Even though the bioplastics are multibillion-dollar industry, there are several challenging factors, which affect the popularity of bioplastics and limits its applications. Mainly the price, marketing activities, investment cost and the technological innovations are affecting the popularity of bioplastics [6]. For instance, at present one kg of bioplastic costs around 1.14 – 21.5 euros and the same amount of conventional plastic costs around 0.57 – 1.59 euros [31] [32].

According to the market research conventional plastics like PP, PE and PET are the most widely used types of plastics in the market and it takes 56.7% from the conventional plastic market [1]. Similarly, bioplastics like bio-PP, bio-PE, bio-PET, PHA and PLA are taking around than 60% of the bioplastic market [1] and it also estimated to increase up to 63% which is around 1 million tons per year in 2025 [30].

The bioplastic market is widely expanding. People and industries are investing to move for more sustainable products and therefore, it is estimated that bioplastic market will expand to 2.87 million tons per year in 2025 from the current market of 2.11 million tons per year [30].

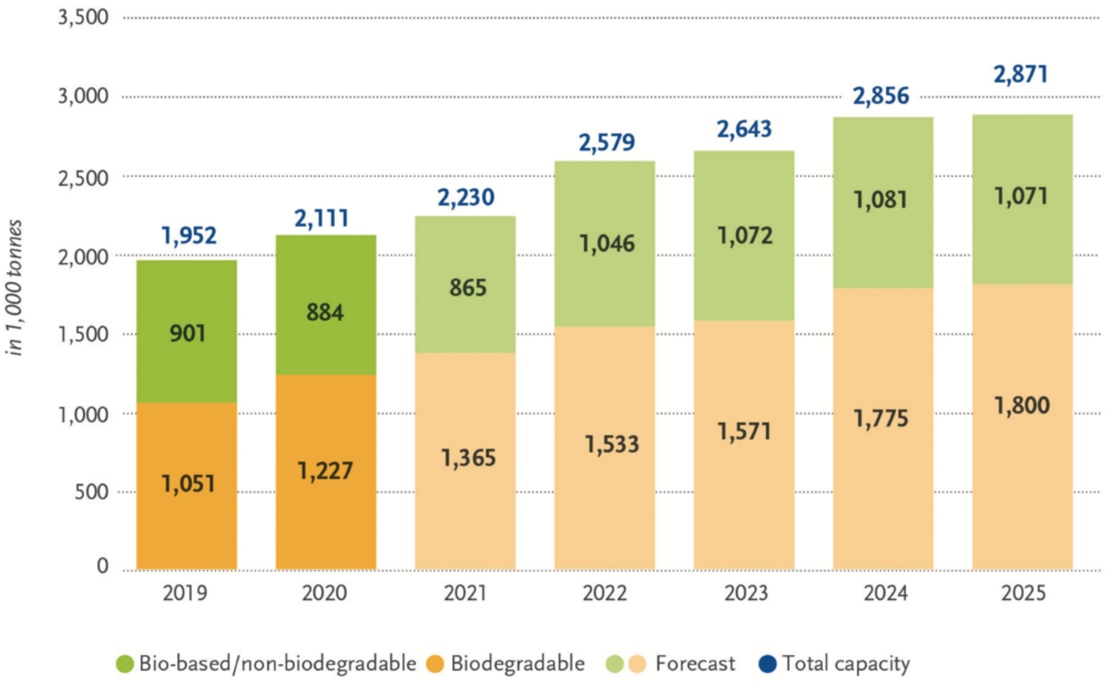


Figure 5: Global production capacities of bioplastic [30]

In present bioplastic market PLA is the most prominent and highest growing types of bioplastics available in the market (Figure 6) [6] [31].

Asia is the leading industrial scale bioplastic manufacturer in the world that manufactured 45% from the global production. Europe, north America, and south American continents manufacture 25%, 18% and 12% respectively [31]. As a country Thailand is the leading country which has the highest percentage of bioplastic production rate compared to its total plastic manufacturing amount which is 49%. This percentage in Europe and United states of America is 22% and 25% [28].

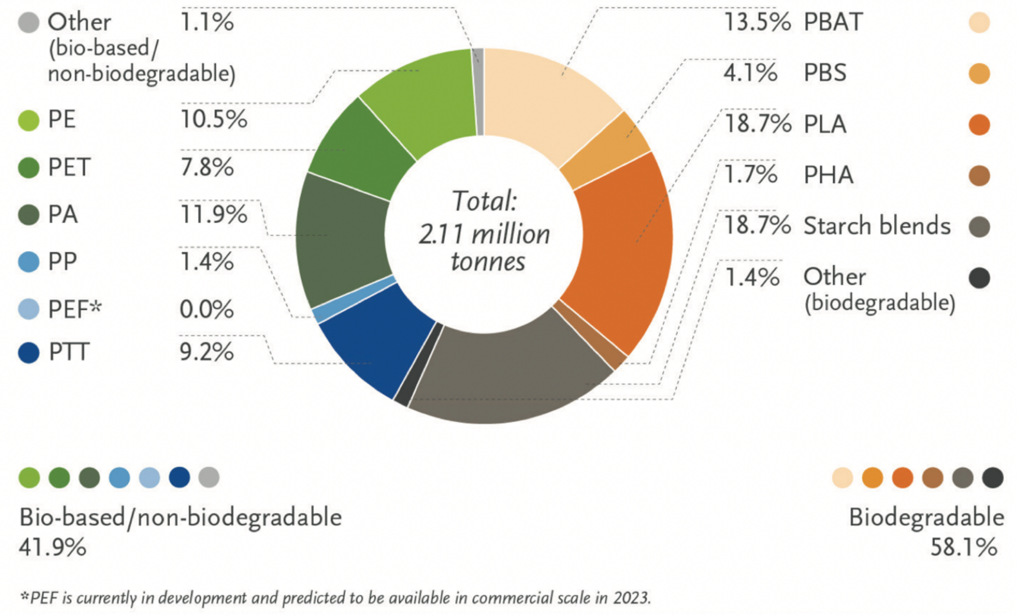


Figure 6:Global production capacities of bioplastics 2020 (by material type) [30]

Around 60% of bioplastics used in the packaging industry, consumer goods industry and textile industry (Figure 7) [33] [30].

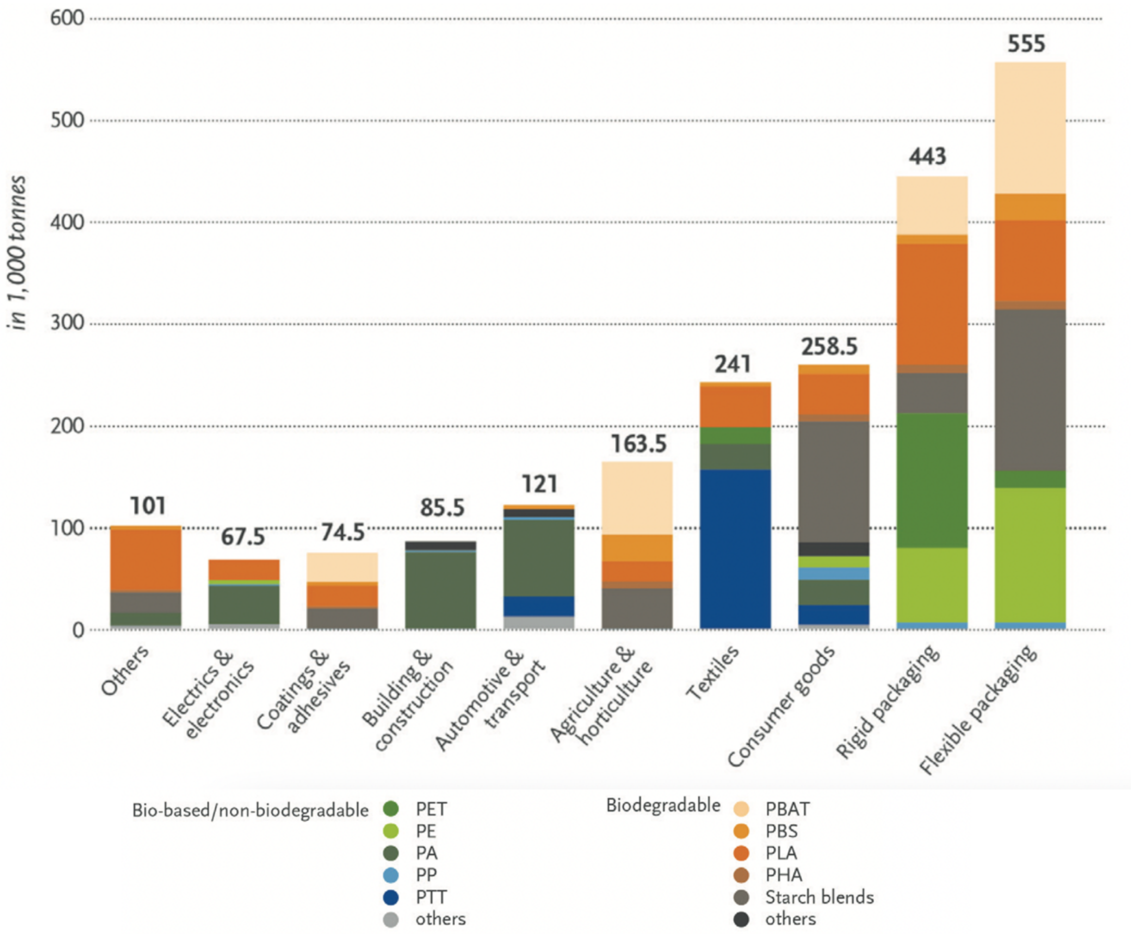


Figure 7: Global production capacities of bioplastics 2020 by market segment [30]

2.2.3 Advantages of bioplastics

Compared to the conventional plastics there are large number of advantages in bioplastics to become the future of plastic manufacturing industry. When it comes to the environmental sustainability, bio based, and biodegradable plastics are on the top of the list.

Producing conventional plastics from petroleum-based products consumed large amount of energy in the process and emits high amount of carbon dioxide and toxic by-products into the atmosphere [34]. But bio-based plastics do not consume that level of energy in the process, because the base carbon chains are already made by some type of biomass. Similarly, bioplastic production does not emit toxic compounds into the atmosphere and release quite low amount of CO_2 into the environment compared to the traditional plastics. Specially to the scarcity of fossil fuels, bioplastics are the most convenient solution in the future of plastic products [35]. Bioplastics can easily use recycled materials and other by-products from different industries like agriculture reducing CO_2 emissions and becoming more energy efficient [34].

The biggest positive side of bioplastics is even though there is no proper waste management system, bioplastics can be designed to be degradable in nature into CO_2, CH4 and H2O in several months or in several years [36]. This property will not increase the accumulation of garbage mountains filled with plastic products [37]. Similarly, the fast rate of biodegradability will reduce the landfill gasses like CO_2 and CH4 because of the conversion of cellulose and other biological carbon chains are consumed by the bacteria and other microorganisms [36].

Sustainable management of bioplastic waste is much easier to the municipal councils, it can be easily converted into compost or biofuel by aerobic and anaerobic digestion [38].

In general, bioplastics have benefits to the human health and well-being for all the animals and plants in the environment. It will not pollute water resources like conventional plastics, save the life in the water and on land, encourage to develop sustainable cities and communities and improve the quality of life of people [37].

2.2.4 Legislative controls for bioplastic

Even though bioplastics are a sustainable solution, the management of bioplastics have to be regulated to optimise the benefits to the environment and minimise the potential risks.

In European union, there are two parallel directives which regulate the single use plastics and plastics bags which are indirectly promoting the bioplastics. The "European green deal" and the "New circular economy action plan" published by the European commission announced a policy framework for sourcing, labelling and use of bioplastics [39].

The objective of these EU initiatives is to promote bioplastics genuinely lead for environmental benefits and to contribute for a sustainable plastic economy [39].

Some countries like Italy and France have banned their use of non-biodegradable and disposable plastic carrier bags and single use plastic items made from conventional plastics in their day-to-day use [40].

2.2.5 Current bioplastic drawbacks

There are a lot of areas needed to be developed in the bioplastic industry in the present situation. There are several drawbacks and considerable issues in the existing bioplastic products and the manufacturing process, which need to be improved to become a more reliable and popular product in the market.

One of the most concern disadvantage of bioplastic is the production process which is quite complex and expensive. The main reason for the cost of production is still bioplastics are in its early stage of development and there are lots of ongoing research to develop the process [41]. This issue limits the commercial applications of bioplastics and ultimately the cost of bioplastic product is 2 or more times higher than the ordinary plastic product [42] [43] [4]. But in future with the large-scale production and modified production processes this issue can be solved.

Next reason why bioplastics are not a viable product at the market now is its poor performance compared to the conventional plastics and poor mechanical properties of it [43] [4]. For instance, bioplastics like PBSA has low resistance with liquids and poor compatibility between liquid and solid phase. Most commonly this hydrophobic quality occurs due to the agricultural biomass used to manufacture the bio-based plastics [41].

When degrading biodegradable plastics in the natural environment by the bacteria or other microorganisms, the nature should be neutral to those microorganisms with the absence of ecotoxic substances [44]. But in most of the landfill sites the soil is contaminated with synthetic chemical compounds which are not suitable for microbial growth, and it will limit or slow down the process. Therefore, it will affect to the proper biodegradation of bioplastics which will limit the main purpose of innovative bioplastics use to reduce the environmental impacts. There are very limited facilities to recycle or compost bioplastics in the world. The bioplastics mixed with conventional plastics also not suitable for recycling both types, specially it will impact the current traditional plastic recycling processes. Therefore, until developing new facilities to proper recycle of bioplastics, these problems will remain as a drawback [42] [44].

Bio-based plastics are made out from the renewable sources like corn, sugar, rice etc. High production rate of bio-based plastics from those kinds of sources will increase the scarcity of those sources and the price will be increased to the regular customers of those products. Use of agricultural products which can consume by people will also become a problem in future when bioplastics become widely popular product [42] [43] [4] [44].

Lack of governmental policies and legislative regulations of production, usage and waste management of bioplastics bring the lack of awareness among the people about the term of bioplastic in the market [42]. Businesses are taking this advantage to increase their profits by marketing all plastic products as environmentally friendly bioplastics. All bioplastics are not biodegradable and due to the lack of information and low availability of biodegradable plastics in the market, traditional plastics still dominate in the packaging industry [4].

2.3 Recognized methods of biodegradability testing of bioplastics

Biodegradability can be tested in several ways according to the standards. For instance, according to the international union for pure and applied chemistry biodegradable polymers are "susceptible to degradation by biological activity with the degradation accompanied by a lowering its mass". In other organisations biodegradability is defined as "complete mineralisation of the plastic to CO_2, water and biomass". The second definition used in EU and most of the other developed countries [40].

Biodegradability can be measured by the carbon dioxide emitted from the bioplastic materials converted by the microorganisms in aerobic environment. In the anaerobic environment the level of conversion is determined by the biogas or methane emitted during the process [45]. According to the EN 14046 standard the acceptance level biodegradability is 90% and it should reach within 6 months in controlled environment (temperature 58C, humidity 50%, air circulation to maintain 6% O2) [45].

There are several testing methods and standards available in different standards to measure the biodegradability of bioplastics.

Table 2: Standards to assess biodegradation of plastics and bioplastics [45]

Standard	Brief description and aim
ISO 20200	Testing method to determine the disintegration degree of plastic materials in composting
ISO 16929	Test method to determine the degree if disintegration of plastic materials in a pilot scale aerobic composting environment
ISO 14855	Test method to determine the ultimate aerobic biodegradability of plastic and the degree of disintegration under controlled composting conditions
EN ISO 14851	Test method to determine the aerobic biodegradability of plastic materials by measuring the oxygen demand in a close respirometer

EN 14806	Test method to determine the disintegration degree of plastic materials in composting
EN 14045	Test method to evaluate the disintegration of packing materials in a pilot scale aerobic composting test
EN 13432	Test method to determine the compostability and the anaerobic treatability of packing material
ASTM D5338	Testing method to determine the ultimate aerobic biodegradability of plastic and the degree of disintegration under controlled composting conditions

2.3.1 Aerobic biodegradation process

Decomposing organic matters by the microorganisms in the presence of oxygen is called aerobic biodegradation process. By this process, carbon dioxide, water, heat and compost from the organic matter is produced. The organic matter is consumed by the microorganisms as the energy source for their growth in the aerobic environment and decompose high molecular weight and oligomeric substance into primary substances. Mainly Bacteria and fungi naturally exists in the environment is participating in this process [46]. The simplified reaction illustrated by following equation.

$\text{Organic matter} + S + O_2 \leftrightarrow CO_2 + H_2O + NO_2 + SO_2 + \text{Heat} + \text{Compost}$ [47]

Compost contains high quality humus which can be used as organic fertilizers for the agricultural industry. In the process of composting, microorganisms increase the content of nitrogen and phosphorus which can absorb to the plants. Also using the organic waste like food waste, wood, and other agricultural waste as the raw material for the composting production will help to minimise the environmental pollution and solid waste accumulation in the landfills [46].

To get high quality compost from the composting process, the system needs to maintain optimal temperature, moisture content, and oxygen, C/N ratio for 4 to 18 months with continuous monitoring and controlling to maintain the conditions suitable for the microbial activities. Specially the organic waste that are using for the composting process need to have at least 25% of easily degradable organic material to start the composting process by microorganisms. Moisture content should be around 60%, optimal pH level is around 8.5 and oxygen concentration around 6% are the main process conditions. During the process of composting, microorganisms generate heat around temperature 40 – 65 ^{0}C. The initial C/N ratio should be in the range of 20 to 30 [47].

Composting process has four main stages [48].

1. Mesophilic warming up phase (25 – 40 ^{0}C)
2. Thermophilic phase (40 – 65 ^{0}C)
3. Cooling phase
4. Compost maturation phase

During the first step Mesophilic warming up phase of composting, the temperature of the mixture gradually increases up to 40 ^{0}C and population of microorganisms are increasing exponentially because there are lots of food sources are available for the microbes [49] [50].

In the second stage of the composting process, the temperature rises to 60 ^{0}C which is why it is call thermophilic stage. Controlling moisture and oxygen during this stage is a key important parameter to maintain the microbial population for the composting process. During this stage, easily biodegradable organic matter is consumed by the microorganisms and break the complex structures. To have homogeneous mixture of compost, maintaining temperature and other parameters are very important. [49] [50].

In the third step of composting, the temperature starts to decrease around 40 ^{0}C again and compost will be re-invaded by mesophilic microorganism and nitrifying bacteria. They start to consume the other hardly biodegradable organic matter due to lack of easily degradable organic matter [49] [50].

In the final stage of composting, final compost product start to stabilize and maturing due to slowing down of composting process by the microorganisms. As a result, humic substance start to increase under the presence of soil microbes [49] [50].

Aerobic composting is an exothermic process, during which mass is heated and thermal energy is released. Biodegradable components like cellulose, hemicellulose, proteins, biopolymers, individual pesticides are natural decomposition material converted into final products of compost, $CO_{2,}$ and water after the composting process [51].

2.3.2 Anaerobic biodegradation process

Anaerobic biodegradation process is digesting organic matter by the anaerobic microorganisms’ presence in the environment with the absence of oxygen. These microorganisms convert the organic waste into biogas which contains methane and carbon dioxide. Anaerobic bacteria participating in the biodegradation process are highly sensitive to the temperature and therefore, controlling temperature is key parameter of this anaerobic biodegradation process. The biodegradation process divides into three main steps based on the operating temperature: psychrophilic (10 -25 ^{0}C), mesophilic (25 – 40 ^{0}C) and thermophilic (52 – 55 ^{0}C). Optimal humidity level needs to operate anaerobic digesting process is around 92 – 93%. Most suitable temperature for anaerobic process is between 25 – 40 ^{0}C and in some cases it rises to 55- 60 ^{0}C depending on the technology and process. The production and composition of biogas depends on the parameters like temperature, humidity, and the impurities [46].

In industrial applications, to start the digesting process, organic solid waste is mixing with sludge from a wastewater treatment plant and makes a complex anaerobic ecosystem, where anaerobic bacteria can consume organic matter for their growth. The remaining waste is called digestate, which is using for the agricultural applications as a fertilizer. Following equation is showing the main reaction occurs during an anaerobic digesting process [47] [52].

Organic matter + H_2O + Nutrients → Digestate residue + CO_2 + CH_4 + NH_3 + H_2S + Heat [47]

There are 3 main stages in the anaerobic biodegradation process [47].

1. Hydrolysis
2. Fermentation
3. Methane formation

In the hydrolysis step microorganisms separate insoluble organic matter like lignin, oil and fat, and carbohydrates into simple substances like sugar [47] [52].

In the fermentation step microbes are increasing the population and dissolving components like fatty acids, amino acids, etc into intermediate products like volatile acids, ammonia, alcohol, hydrogen, and carbon dioxide [47].

In the final methane formation step the produced intermediate products are converting into biogas which is containing methane and carbon dioxide [47].

Biogas produced from the anaerobic biodegradation process is one of the most popular energy sources in the world. It contains methane to generate energy by incineration. In general biogas contains around 55 – 75% of methane depending on the quality of organic matter used and the controlled conditions. Carbon dioxide, hydrogen, nitrogen, and hydrogen sulphide are around 30 – 40%, 5 – 10%, 1 – 2% and less than 1% respectively in the biogas mixture. There are developed systems and technologies to produce biogas with more than 95% of methane [47].

The optimum level of pH for the anaerobic process in between 6.4 to 7.2. For the fermentation stage the pH should be not less than 6.4 and for the methane formation step it should be in between 6.6 to 7 [47].

The optimum C/N ratio for the microbial activities in the anaerobic process is from 20:1 to 30:1. Most of the anaerobic bacteria is sensitive for the toxic substance and to maintain good quality biogas output, it is necessary to maintain a toxic free environment [47].

The biogas produced by anaerobic process has advantages in producing energy compared to the aerobic process. And this process does not have odours or fumes during the process, which makes more convenient and flexible. But the process is complex, and it has higher cost compared to aerobic degradation. The digesting period also longer than the composting process [52] [47].

3 Methods and Materials

3.1 Materials

3.1.1 Compost

For the biodegradability testing of bioplastic materials, matured compost was used which was taken from the Keila wastewater treatment plant in Estonia.

Main parameters need to check before using compost as inoculum

1. **Ph** – one part of compost was mixed with 5 parts of deionised water measured the pH immediately with the pH meter. According to the ISO 14855-1:2012 standard, pH should be in between 7 – 9.

   Actual pH level = 7.1

2. **Total Dry Solids (TDS)** – weighted amount of compost sample was taken and dried at 105 ^{0}C inside the incubator. Final weight was measured, and the total dry solids content should be in between 45 – 55% of wet solids. If the moisture content is low, increase the moisture level by adding water or if the moisture content is high, compost can be dry to adjust the TDS level.

   Average TDS level = 48.93%

3. **Total Volatile Solids (TVS)** – the remain dry solids after drying up to 105 ^{0}C, again place inside the incubator at 550 ^{0}C to measure the TVS. Weight the remaining sample after the incubation period and subtract the value from the TDS value to get the TVS. The TVS should be more than 15% of wet solids.

   Average TVS level = 43.66%

4. **C/N ratio** – C/N ratio of compost can be calculated from the total organic carbon (TOC) content and the total nitrogen content measured separately. C/N ratio should be in between 10 – 40.

   TOC = 47%

   Total nitrogen = 3.4%

$$\frac{C}{N}\,ratio = \frac{47\%}{3.4\%} = 13.8$$

Preparing the compost

The compost should be free from glass, stones, metals, and wooden particles so that removed it manually. Then sieve the compost in a screen of 1 cm to remove the big particles. This will help to increase the porosity between compost which needs for the aerobic conditions.

3.1.2 Cellulose

The cellulose used for the experiment as reference material was Thin Layer Chromatography (THC) grade cellulose powder which has particle size of less than 20 micrometres.

Main parameters need to check before using cellulose as reference material

1. **TDS**

	Wet solids	After 105 ^{0}C	TDS %
Sample 1	1.9903	1.8135	91.12%
Sample 2	2.0176	1.8288	90.64%
Sample 3	2.233	2.0224	90.57%

Average TDS level = 90.78%

2. **TVS**

	After 105 ^{0}C	After 550 ^{0}C	TVS %
Sample 1	1.8135	1.8079	99.69%
Sample 2	1.8288	1.8241	99.74%
Sample 3	2.0224	2.0166	99.71%

Average TVS level = 99.72%

3. **Total organic carbon (TOC)** – There should be sufficient organic carbon to produce CO_2 during the degradation process to identify. For that normally 20g of TOC should be in 50g of dry solids.

TOC = 44%

3.2 Aerobic biodegradability testing

Determination the biodegradability of bioplastic materials under the aerobic environment is carried out according to the ISO 14855-1:2012 standard approved by the European committee for standardization.

3.2.1 Test environment

The test environment is needed to be a controlled environment which has dark lighting, and the temperature of $58 \pm 2\ ^{0}$C. The continuous temperature was maintained by a thermal bath.

The environment was free from vaporous inhibitory which can cause impacts on microorganisms.

3.2.2 Apparatus needed

- **Composting vessels** - Glass bottle with 2 litres volume which allows even gas purge in an upward direction. 6 bottles are required for compost and cellulose, 3 bottles each.

- **Ari supply system** – Small air pump with maximum 1.2 l/min flow rate which can controlled as per the need and 0.01 MPa pressure which is capable to supply atmospheric air to each composting vessel to make sure to provide pre-set flow rate high enough to provide aerobic environment. 20-40 ml/min in outlet.

- **Gas tight tubes** – To connect the air pumps and the vessels.

- **Incubator** – To dry the samples up to 105 and 550 ^{0}C to measure the TDS and TVS.

- **Electric Balance** – To measure the weight of samples.

- **pH meter** – To measure the pH of compost.

- **Air Analytical equipment** – To measure the oxygen level.

- **Apparatus for determination of CO_2** – To measure the cumulative carbon dioxide evolved as dissolved inorganic carbon after absorption in sodium hydroxide solution.

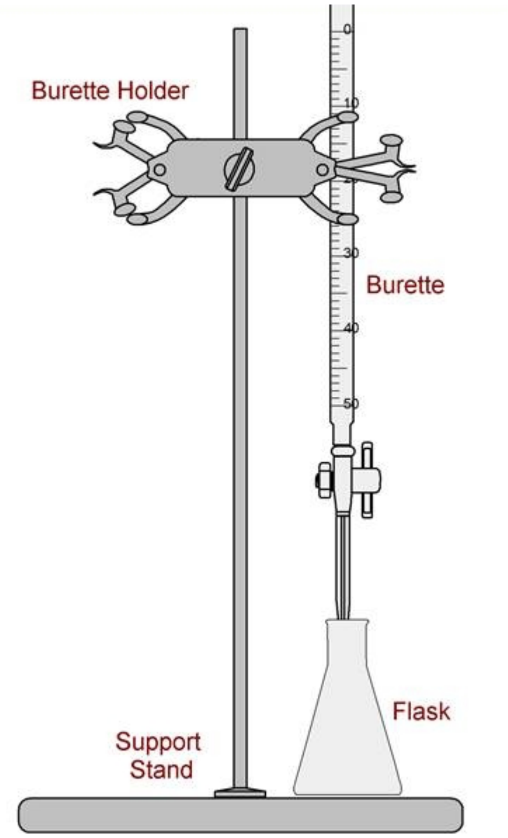


Figure 8: Titrating apparatus [53]

3.2.3 Procedure

Three sets of composting vessels are needed to carry out the biodegradability testing of bioplastic materials.

1. Three vessels for blank compost
2. Three vessels for reference material
3. Three vessels for test material

First ensure all the glassware is properly cleaned and free from organic or toxic matter.

The dry mass of the compost to the test material should be 6:1 ratio and each vessel contained same amount of compost including the blank sample. Add all testing materials about three quarters of the volume form the composting bottle and leave the space above the compost to manually shake time to time.

Table 3: Weights of 6 aerobic composting bottles

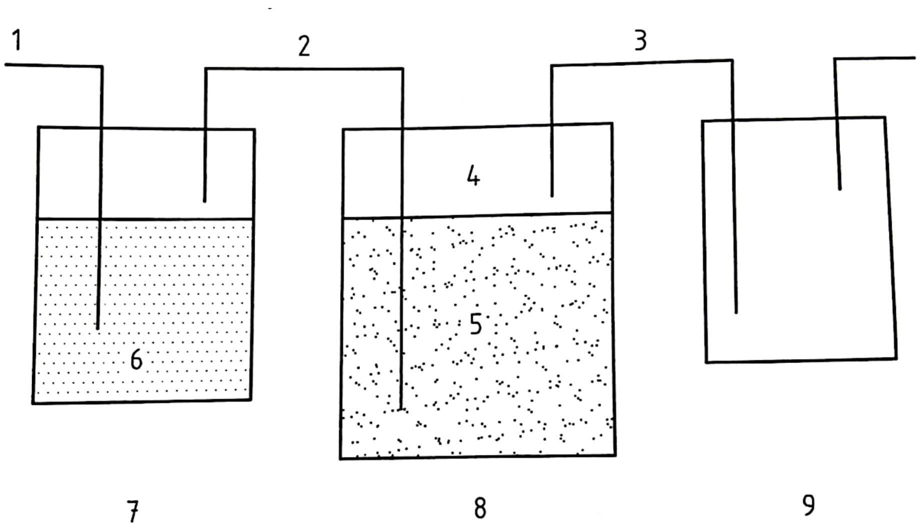
Vessel No.	Sample	Empty vessel weight	Reference material weight	Total weight of bottle	Compost weight
1	Compost (Blank)	992	-	1860	868
2	Compost (Blank)	987	-	1819	832
3	Compost (Blank)	988	-	1822	834
4	Compost + Cellulose	983.2	48.5	1758.5	726.8
5	Compost + Cellulose	982.9	48.5	1755.3	723.9
6	Compost + Cellulose	980.5	48.5	1763.4	734.4

Place the composting vessels in the hot water bath to maintain a constant temperature which is 58±2 ^{0}C, and initiate aeration from the pump after water saturation and CO_2 removing by passing the air through wash-bottles filled with 0.5M sodium hydroxide solution (NaOH aq.).

Collect the CO_2 producing by the composting process by dissolving the gas in 0.2M potassium hydroxide solution (KOH aq.).

The carbon dioxide produced is constantly monitored, and measured at regular intervals, in test and blank vessels to determine the cumulative CO_2 production. Aerobic conditions were maintained during the test in each composting bottle, by checking the air flow regularly at each outlet to make sure there is no leaks in the system.

Maintain the oxygen concentration level always above 6%, to maintain the aerobic conditions. Oxygen levels should closely monitor and adjust air flow rates accordingly.



1. air
2. CO_2 free air
3. exhaust air
4. headspace
5. test material
6. NaOH solution
7. CO_2 removal system
8. composting vessel
9. CO_2 determination system

Figure 9: Layout of aerobic test system according to ISO 14855-1:2012 standard [54]

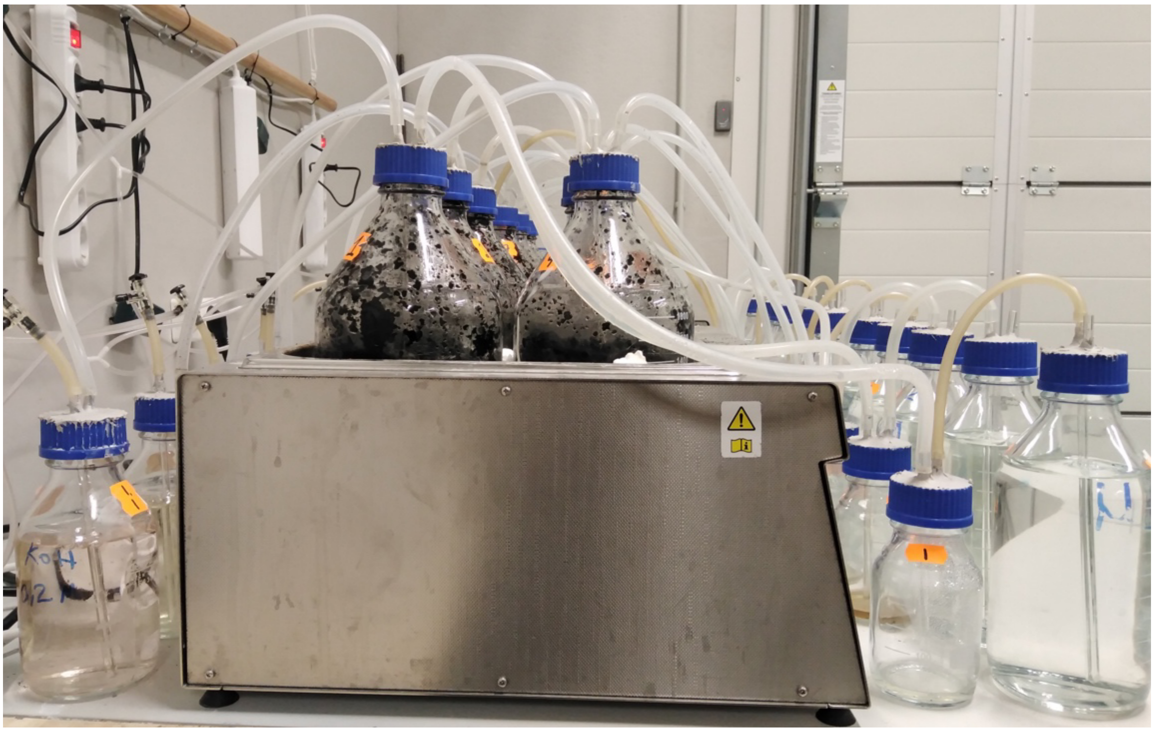


Figure 10: Actual aerobic test system

3.2.4 Incubation period

Carbon dioxide was measured once per day and all the composting vessels were shacked once a week to ensure even distribution of compost, plastic material, air and moisture.

Composting vessels were incubated for 3 months at the constant temperature of 58±2 ^{0}C while recording the CO_2 emissions to make sure full-scale composting.

3.2.5 Calculations

Measuring the CO_2 evolved

Carbon dioxide evolved from the composting vessels were evaluated by the titration method. Three parallel samples were used to measure the amount of carbon dioxide according to the following procedure and calculated the simple average of those three values.

CO_2 react with KOH as: $2KOH + CO_2 \rightarrow K_2CO_3 + H_2O$

In the KOH solution which used to absorb CO_2 c both unreacted KOH and K_2CO_3

During titration, both KOH and K_2CO_3 will react with HCL as follows in 2 different pH ranges,

$KOH + HCL \rightarrow KCL + H_2O$; PH 7

$K_2CO_3 + HCL \rightarrow KHCO_3 + KCl$; PH 8.5

By using 2 indicators (phenolphthalein and methyl orange), which can be used in pH 7 and 8.5 to measure the KOH and K_2CO_3 volumes. From the colour difference in both ranges, HCl volume can be measure and it can be used to calculate CO_2 emitted from the composting process as follows.

CO_2 mol = $\{V_{HCL\,(2)} - V_{HCL\,(1)}\} * [HCL]$

$V_{HCL\,(2)}$ – is the volume of HCL consumed until pH range 8.5

$V_{HCL\,(1)}$– is the volume of HCL consumed until pH range 7

[HCL] – concentration of the HCL (0.2 mol/l)

CO_2 weight = CO_2 mol × 44 g/mol

Calculation of biodegradation

First the theoretical amount of carbon dioxide $ThCO_2$ in grams per vessel which can be produced by the reference material was calculated using the following equation [54].

$$ThCO_2 = M_{TOT} \times C_{TOT} \times \frac{44}{12} \qquad \text{(Equation 1)}$$

M_{TOT} – Total dry solids (g) in the reference material introduced into the composting vessels at the start of the test

C_{TOT} –Proportion of total organic carbon in the total dry solids in the reference material

44 and 12 – are the molecular mass of carbon dioxide and the atomic mass of carbon

From the cumulative amounts of carbon dioxide released, the percentage biodegradation D_t of the reference material was calculated using the following equation [54].

$$D_t = \frac{(CO_2)_T - (CO_2)_B}{ThCO_2} \times 100 \qquad \text{(Equation 2)}$$

$(CO_2)_T$ – Mean cumulative amount of CO_2 evolved in composting vessel containing reference material

$(CO_2)_B$ – Mean cumulative amount of CO_2 evolved in the blank composting vessels

$ThCO_2$ – Theoretical amount of CO_2 which can be produced by the reference material

3.3 Anaerobic biodegradability testing

Determination the biodegradability of bioplastic materials under the anaerobic environment is carried out according to the ISO 15985: 2014 standard approved by the European committee for standardization.

3.3.1 Test environment

The test environment is needed to be a controlled environment which has dark lighting, and the temperature of 52±2 ^{0}C. The continuous temperature was maintained by a thermal bath.

The environment was free from vaporous inhibitory which can cause impacts on microorganisms.

3.3.2 Apparatus needed

- **Digestion vessels** – Glass bottle with 500 millilitres volume which do not allows gas escaping during the process. 6 bottles are required for compost and cellulose, 3 bottles each.

- **Gas volume measuring system** – The releasing biogas was measured by the wet gas flow measuring device. This is working according to the principle of liquid displacement and buoyancy.

- **Incubator** – To dry the samples up to 105 and 550 ^{0}C to measure the TDS and TVS.

- **Electric Balance** – To measure the weight of samples.

- **pH meter** – To measure the pH of compost.

3.3.3 Procedure

Two sets of anaerobic digesting vessels were needed for carry out the biodegradability testing of bioplastic materials as follow.

1. Two vessels for blank controls
2. Two vessels for reference material
3. Two vessels for test material

First ensured all the glassware was properly cleaned and free from organic or toxic matter.

The dry mass of the compost to the test material should be 6:1 ratio and each vessel contained same amount of compost including the blank sample. Added all testing materials about three quarters of the volume form the composting bottle and left the space above the compost to manually shake time to time.

Table 4: Weights of anaerobic digesting bottles

Vessel No.	Sample	Empty vessel weight	Reference material weight	Total weight of bottle	Compost weight
1	Compost (Blank)	339	-	539.7	200.7
3	Compost + Cellulose	339.8	14.75	553.9	199.35

Placed the digesting vessels in the hot water bath to maintain a constant temperature which is 52±2 ^{0}C and connected them to the gas measurement device.

The biogas production was constantly monitored and make sure the anaerobic conditions were maintained during the test in each digesting bottle by checking each outlet to make sure there was no leaks in the system.

3.3.4 Incubation period

Biogas volume was measured once per day and all the composting vessels were shacked once a week to ensure even distribution of compost and plastic material.

Composting vessels were incubated for 40 days at the constant temperature of 52±2 ^{0}C while recording the biogas emissions to make sure full-scale anaerobic digestion.

3.3.5 Calculations

Calculation of gaseous carbon

First, the volume of methane evolved from reference samples are converted to volumes at standard conditions (temperature = 273K and pressure 1.013.25 hPa) using the ideal gas equation [55].

$$\frac{pV}{T} = Constant \qquad \text{(Equation 3)}$$

p - pressure

V - volume

T - temperature

The converted volume of biogas is then converted to mass by using the standard equation which is 22.4 ml of biogas at STP = 12 mg of Carbon.

Calculation of the percentage biodegradation

From the cumulative amounts of carbon released, the percentage of biodegradation of the reference material was calculated using the following equation [55].

$$\%\, biodegradation = \frac{m_{C,g}(reference) - m_{C,g}(blank)}{m_{C,I}} \times 100 \qquad \text{(Equation 4)}$$

$m_{C,g}$ - Amount of gaseous carbon evolved

$m_{C,I}$- Amount of carbon initially in the test material (TOC × weight of sample)

4 RESULTS ANALYSIS

4.1 Aerobic Biodegradation

The carbon dioxide evolved from each vessel was measured by the titration process. In the day 1, 1st compost vessel had 8.7ml of HCl reading after the titration. The total volume was 500ml and the sample taken to titrate was 20ml.

$$CO_2\ mass = \left(\frac{8.8}{1000} \times 0.2\right) \times \frac{20}{500} \times 44 = 1.914g$$

After 45 days aerobic composting process in 3 separate biodegrading vessels, blank compost samples were calculated similarly and presented the values in figure 11.

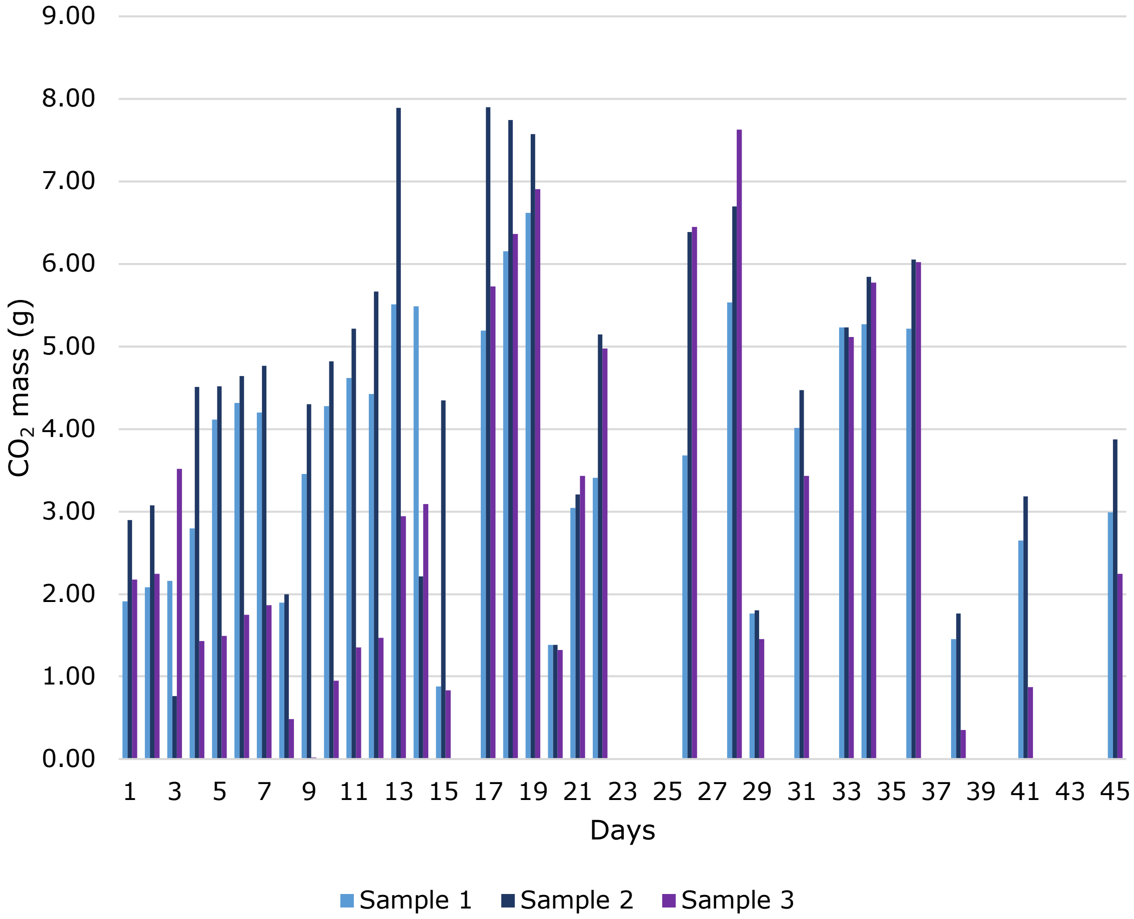


Figure 11: Daily CO_2 production from blank composting vessels

At the beginning of the composting process carbon dioxide release rate is lower than compared to the middle of the composting process. The recorded highest per day of releasing carbon dioxide was 7.9 g and the lowest is 0.35 g per day.

The cumulative amount of carbon dioxide released from each composting vessel presented in Figure 12.

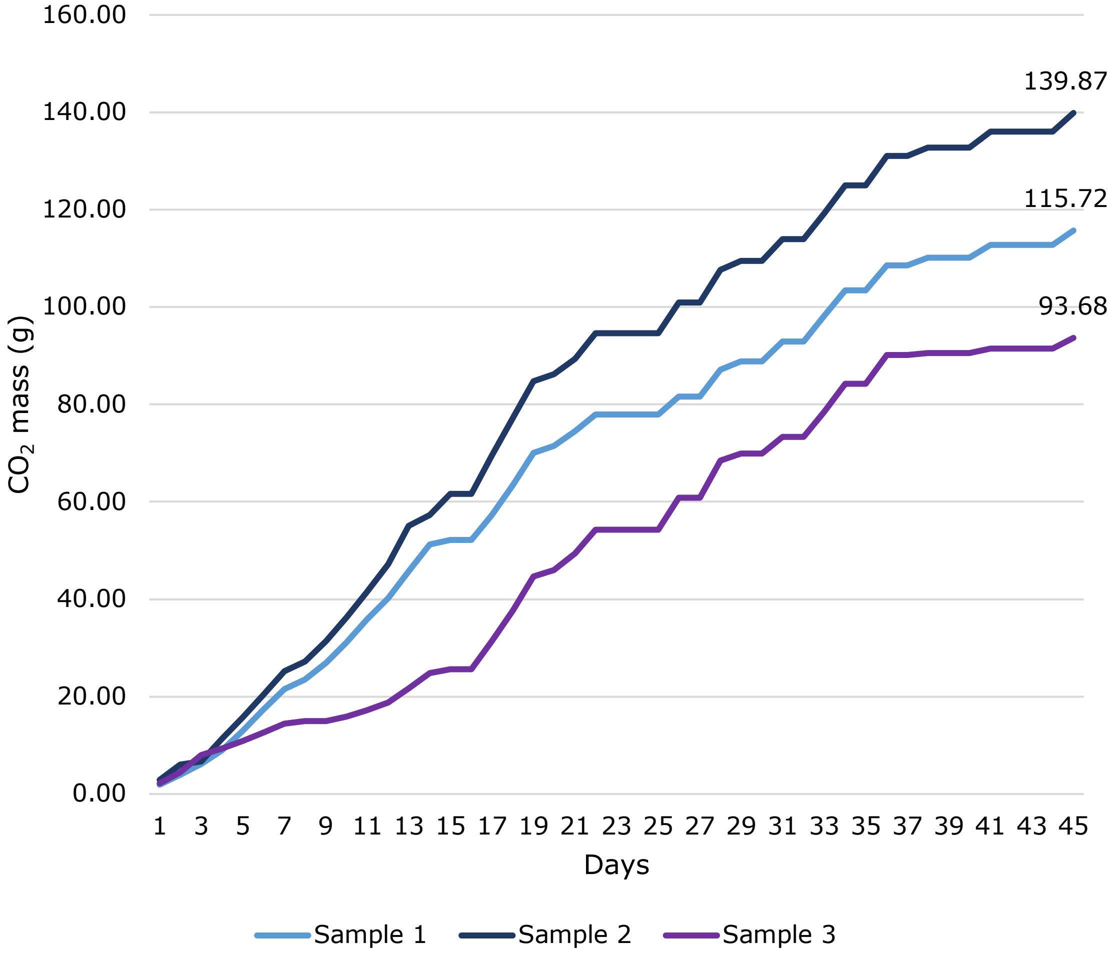


Figure 12: Cumulative CO_2 production from blank composting vessels

After 45 days composting process, 1st blank composting vessel produced 115.72 g of carbon dioxide and the 2nd and 3rd blank composting vessels produced 139.87 g and 93.68 g of carbon dioxide respectively. According to the graphs all 3 blank samples have a similar pattern of biodegrading under the aerobic conditions which has less than 20% of difference to the middle value of 115.72 g in the sample 1.

Figure 13 illustrates the biodegradation of cellulose in compost after 45 days of biodegradation under the aerobic conditions.

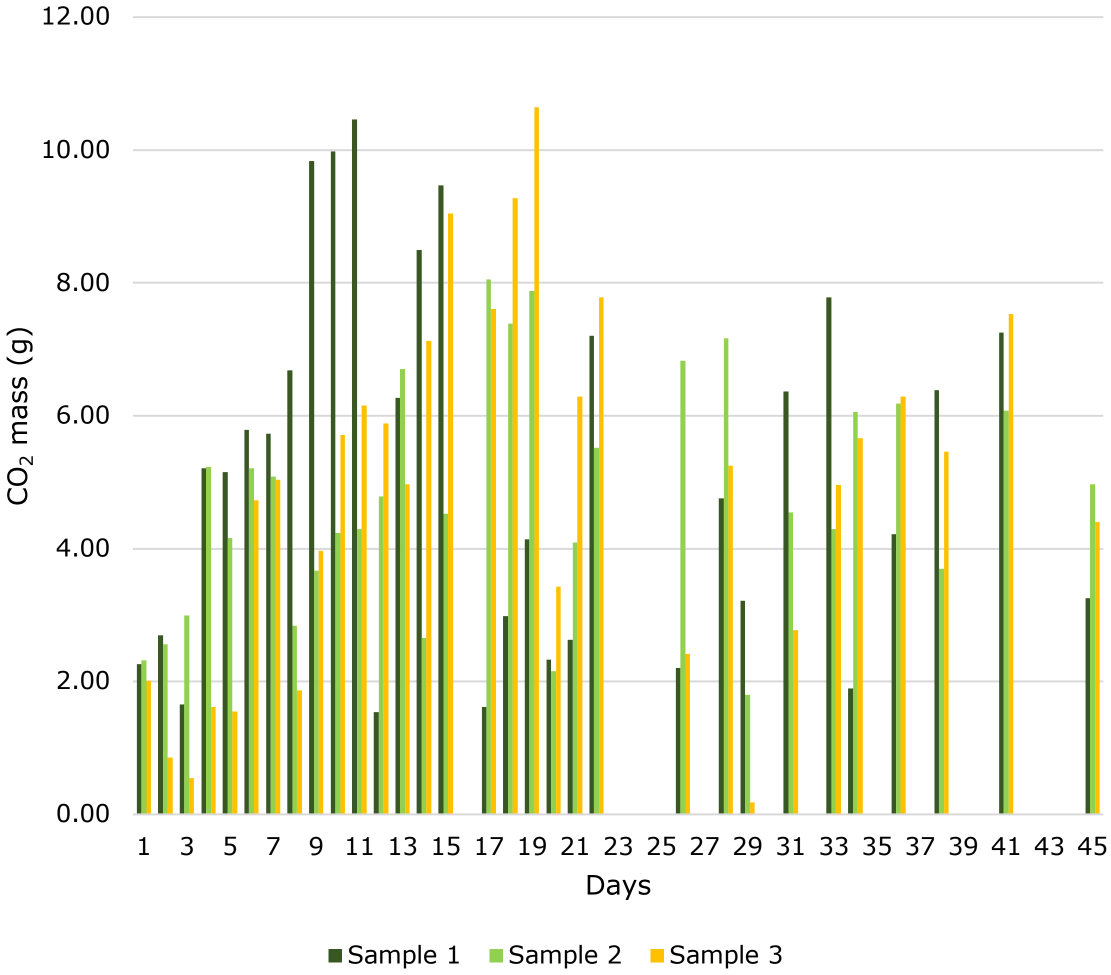


Figure 11: Daily CO_2 production from cellulose + compost vessels

According to the carbon dioxide emission results at the beginning of the process, carbon dioxide production is lower than to the middle days of the process. The highest amount of carbon dioxide produced per day was 10.65 g and the lowest is 0.18 g of carbon dioxide per day.

Cumulative of carbon dioxide produced during the 45 days period of aerobic composting process presented in Figure 14, which is reflecting the total mass of carbon dioxide produced in the biodegradation process.

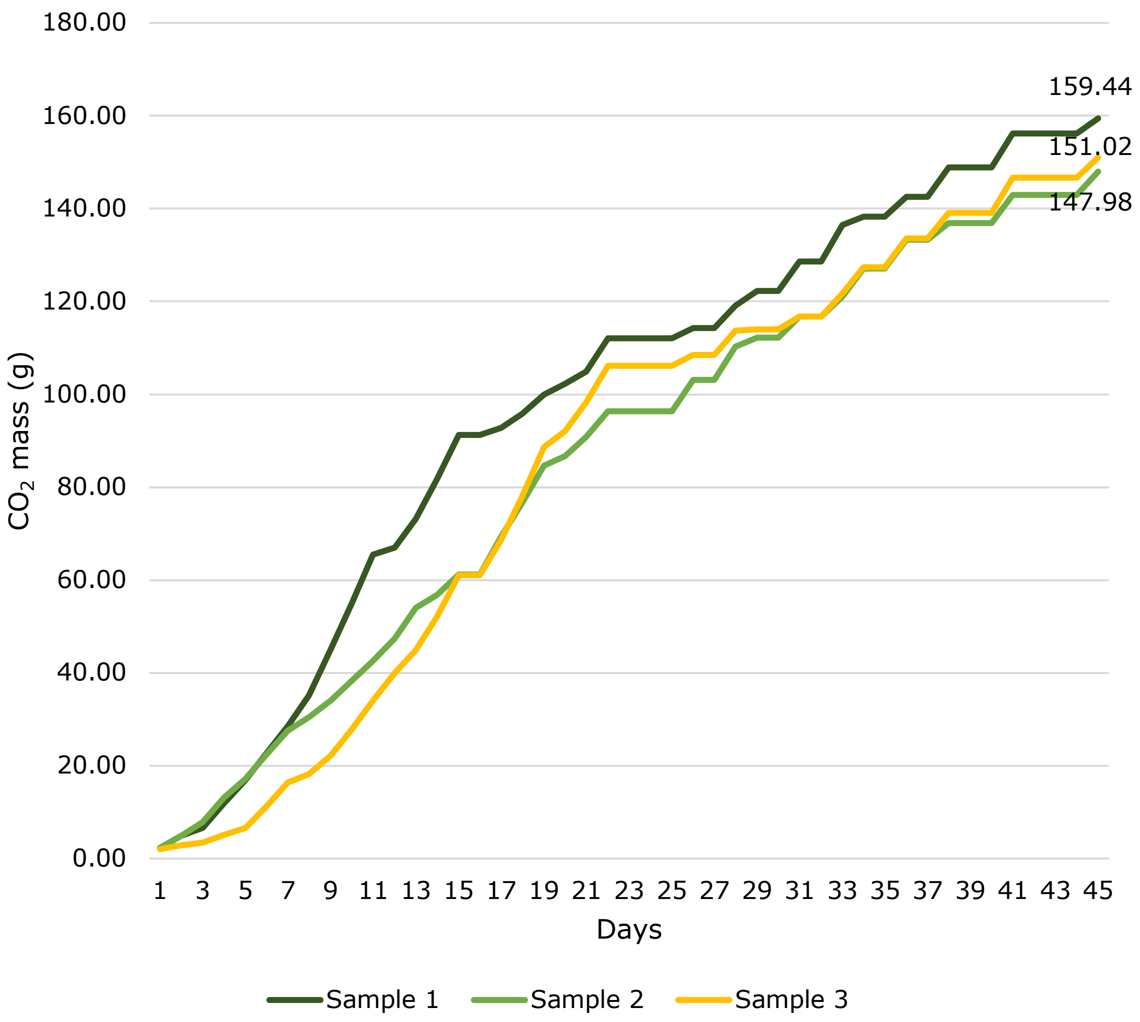


Figure 12: Cumulative CO_2 production from cellulose + compost vessels

Cumulative amount of carbon dioxide produced after 45 days of aerobic biodegradation process from the sample 1, 2, and 3 are 159.44 g, 147.98 g, and 151.02 g respectively. The difference of mass between each sample is less than 6% which made all 3 samples had similar biodegradation process.

Based on the cumulative amount of carbon dioxide produced from the blank compost samples and cellulose + compost samples, the average amount of carbon dioxide production from blank compost samples and cellulose + compost samples can be derived (Figure 15). It reflects the average amount of carbon dioxide produced from blank compost samples and average amount of carbon dioxide produced from the compost + cellulose samples easy to compare.

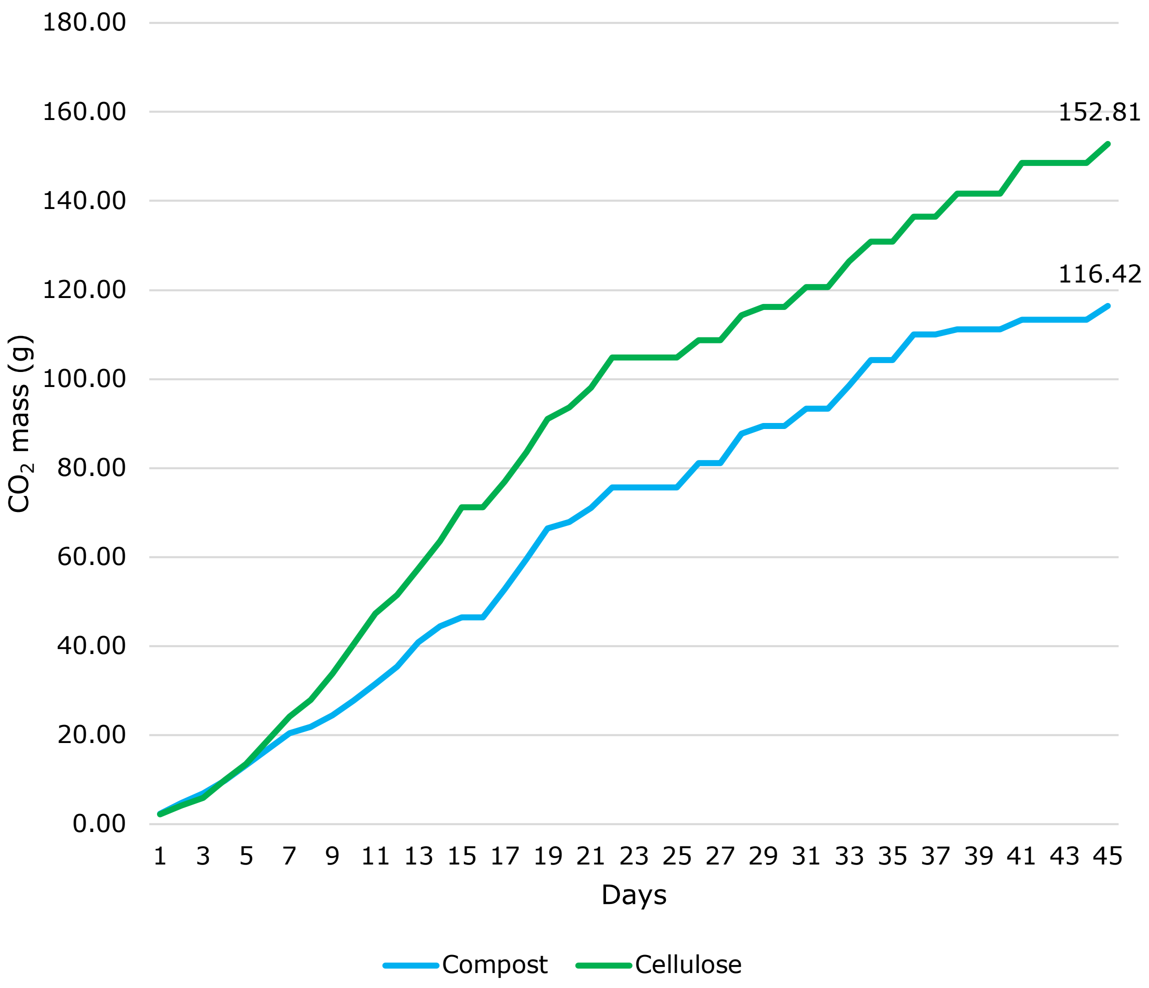


Figure 15: Average CO_2 production from blank compost samples and cellulose + compost samples

According to the graph the total amount of carbon dioxide produced from the blank samples at the end of 45 days is 116.42 g and cellulose + compost samples is 152.81 g.

To calculate the percentage biodegradation of cellulose in compost in the aerobic conditions from equation 1,

$$ThCO_2\ of\ cellulose = 48.5\ \times\ 0.9078\ \times 0.44\ \times \frac{44}{12} = 71.03g$$

The percentage biodegradability of cellulose after 45 days period (equation 2):

$$D_t = \frac{152.81 - 116.42}{71.03} \times 100\% = 51.23\%$$

4.2 Anaerobic Biodegradation

After 40 days of anaerobic digestion, biogas production from the blank compost sample and the (compost + cellulose) sample presented in Figure 16.

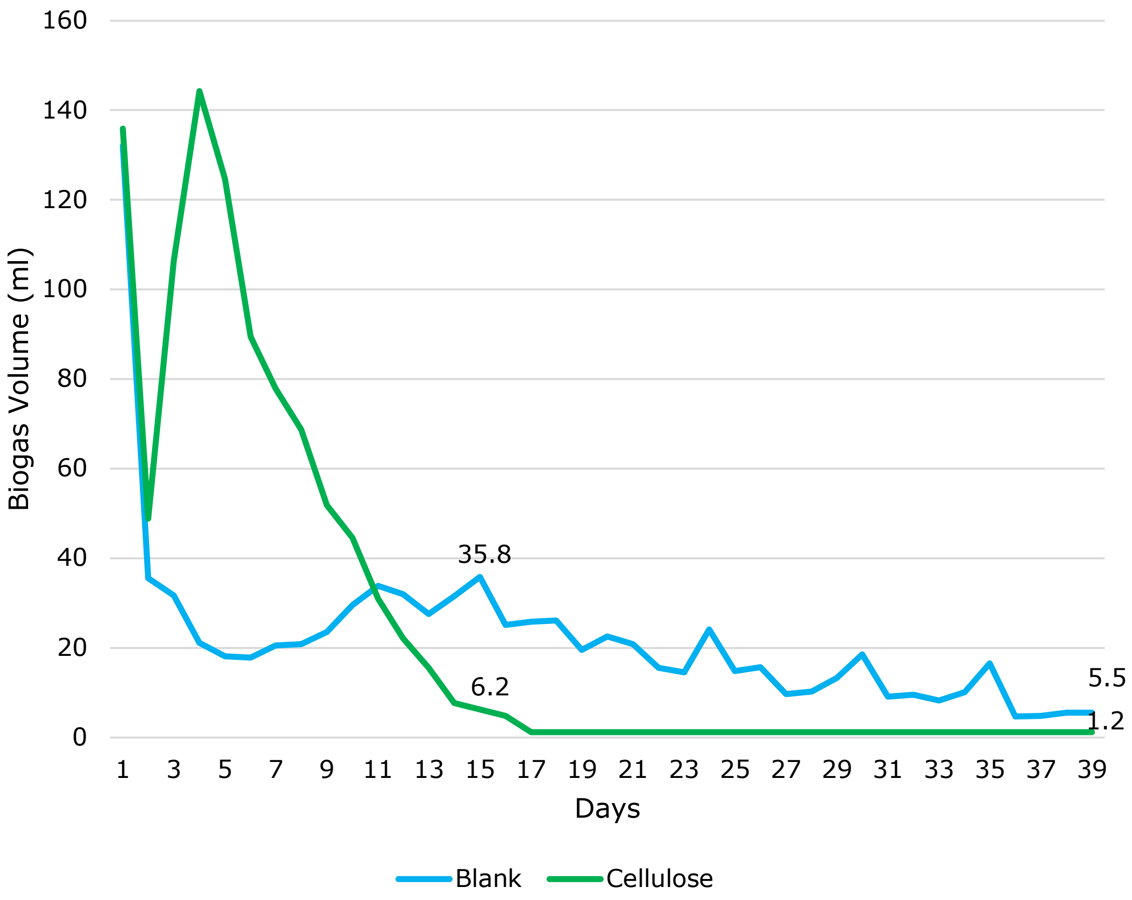


Figure 13: Daily Biogas production from compost sample and compost + cellulose sample

At the start of the process both samples have released large amount of biogas and with the time the amount of biogas releasing reduces. At the end of the experiment period, compost + cellulose sample released 5.5 ml of biogas per day and compost plus cellulose sample released 1.2 ml of biogas per day.

The cumulative of releasing biogas throughout the digestion process illustrated in Figure 17. This diagram reflects the biodegradability of cellulose with respect to the blank compost sample.

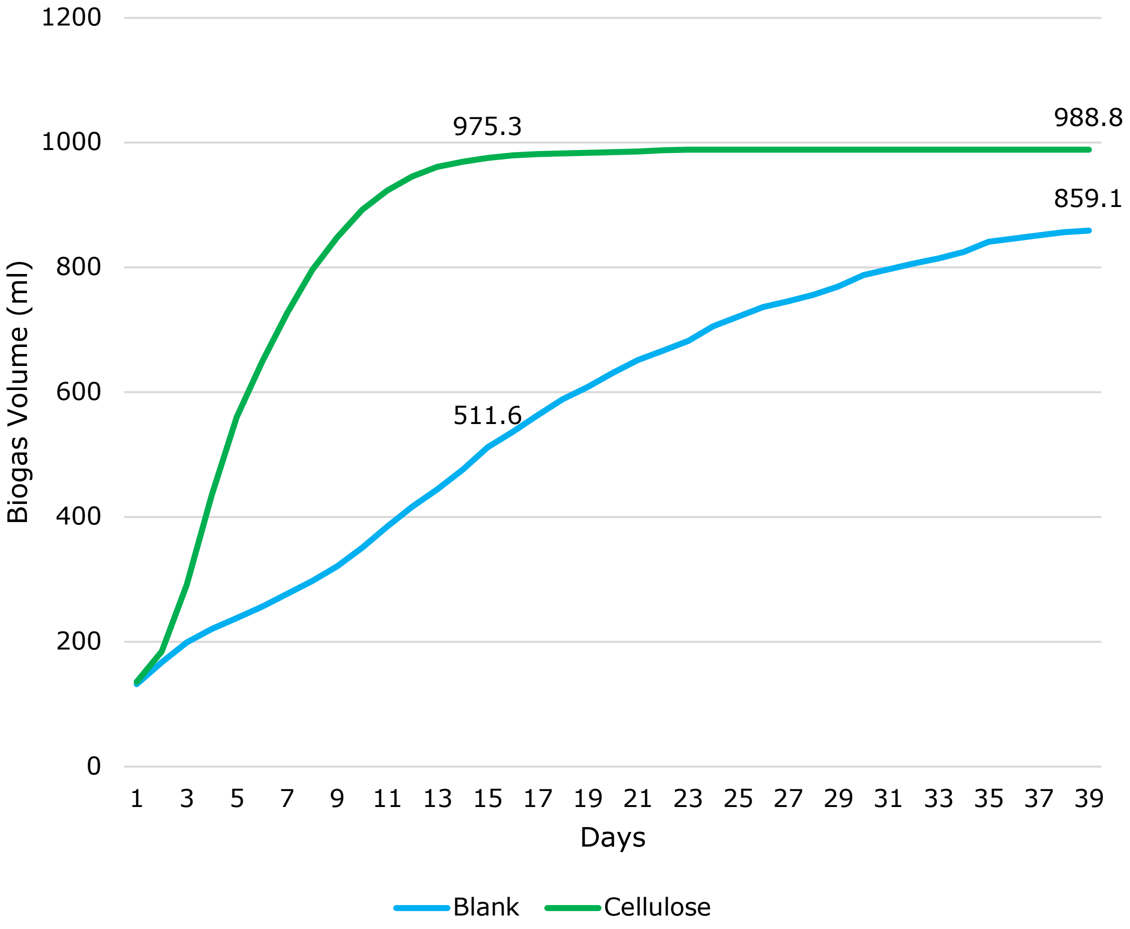


Figure 14: Cumulative biogas production from compost sample and compost and compost + cellulose sample

According to the total biogas amount produced after 40 days of anaerobic digesting process, blank compost sample has released total amount of 859.1 ml of biogas and compost + cellulose sample has released 988.8 ml of biogas.

According to the ISO 15985: 2014 standard, to remark as a successful material to use as reference material, cellulose should degrade more than 70% after 15 days of anaerobic digesting period

According to the total biogas production, after 15 days blank sample has produced 511.6 ml of biogas and compost + cellulose sample has produced 975.3 ml of biogas. Based on these 2 values total biodegradation percentage of cellulose can be calculated by converting volume of biogas by using the standard equation which is 22.4 ml of biogas at STP = 12 mg of Carbon.

$$Biogas\ mass\ (Compost\ vessel) = 511.6ml \times \frac{273K}{(273+52)K} \times \frac{12mg}{22.4ml}$$

$$= 230.22mg$$

$$Biogas\ mass\ (Compost + cellulose\ vessel)$$

$$= 975.3ml \times \frac{273K}{(273+52)K} \times \frac{12mg}{22.4ml} = 438.89mg$$

$$Initial\ carbon\ in\ cellulose = 14.75 \times 0.44 = 6.49g$$

According to the equation 4, the percentage of biodegradation of cellulose:

$$\%\ biodegradation = \frac{438.89mg}{6490mg} \times 100\% = 6.8\%$$

The low biodegradability of cellulose in anaerobic environment was a result of not maintaining the optimum conditions for the bacteria such as higher temperature in the test environment (58 ^{0}C) and the amount of cellulose added to the biodegrading vessel is higher than the optimum ratio. Therefore, this experiment has to be conducted again with more monitoring and controlling methods and more suitable compost and cellulose material.

To be successful, there should be 3 similar blank samples and 3 similar composts + cellulose sample vessels in the anaerobic digesting system. According to the ISO 15985: 2014 standard the difference of percentage of biodegradation between these samples should be less then 20%. Including three similar samples from each to validate the results as described in the standard will make a successful experiment.

5 CONCLUSIONS

This experiment was carried out to determine the biodegradability of new bioplastic materials. For the comparison of results, cellulose was used as a reference material.

In comparison to the blank compost sample, cellulose was degraded only 51.23% in the controlled aerobic environment after 45 days. According to the ISO 14855-1:2012 standard, the reference material has to degrade more than 70% in the similar conditions to evaluate biodegradability of new materials. In the natural composting environments, cellulose is degrading around 65 – 70% [56]. Main reasons for the low biodegradability results from the experiment are,

- Carbon dioxide leakage from the system by lose connections
- Gas escape during the samples taking for titration. Each time taking samples to titrate, the air flow continuously worked and gas was escaping from the system due to that.
- At the start of the experiment the air flow rate was higher than the recommended value which made the gas loss not negligible
- The compost used from the wastewater treatment plant could contain chemicals or heavy metals which are not suitable for the microbes to grow.
- Other human errors of measuring volumes and reading data

To achieve the expected results according to ISO 14855-1:2012 standard, this experiment has to be done again with more monitoring and controlling methods and more suitable compost material.

The test results of cellulose biodegradation in anaerobic environment shows the percentage biodegradability as 6.8%. The level of biodegradability is quite low compared to the expected value of more than 70% after 15 days of period according to the ISO 15985: 2014 standard. The main reasons for the low results are partly similar to the aerobic system which are gas leakages from the lose connections of the testing system and other human errors.

Also, the test environment was not maintained up to the optimum level such as higher operating temperature of (58 ^{0}C) and higher ratio of cellulose with respect to the compost added to the sample. The results were impacted from these errors too. Also, the 2nd attempt of anaerobic test which is progressing at the moment of writing this report shows that cellulose has started its active phase of biodegradation started after 20 – 22 days testing instead of after 15 days. This can be explained because the compost was taken from a wastewater treatment plant, and the anaerobic bacteria population in this compost can be different with the municipal solid waste treatment plant producing compost.

Other than these reasons, anaerobic bacteria are more sensitive to the environmental parameters and slight change of conditions will affect for the population growth and their activities. Similar to the aerobic bacteria, heavy metals and toxic chemicals accumulated in the wastewater sludge can affect the anaerobic process. Because of these reasons, the biodegradability of cellulose in the controlled anaerobic environment is quite low.

The other studies of biodegradability testing, use materials like starch or PE as reference materials too. Starch has TOC level of 38% and PE has TOC level of 85.7% [57]. Depending on the environmental and physical conditions, higher TOC or lower TOC material can be used to increase carbon dioxide production and to get more accurate results.

6 SUMMARY

Conventional plastics are one of the most highlighted issue in the present market due to the accumulation of used products in the soil and water. Bioplastics are one of the common alternatives for replacing conventional plastics as an environmentally friendly product.

Bioplastic composition and the properties can be divided into two main groups according to the raw material which is used to produce or according to the level of biodegradability. Bio-based biodegradable plastics are the most environmentally friendly type to reduce impacts from using conventional polymer products.

Testing the biodegradability of newly developed bioplastics is an important task to identify the level of biodegradability and other impacts that cause to the environment after it introduced to the market.

Biodegradability of bioplastics can be tested in aerobic and anaerobic environment according to the ISO 14855-1:2012 and ISO 15985: 2014 standards respectively. The necessary equipment, chemicals and building the system was carried out according to the ISO standards. Based on the carbon dioxide emission and the biogas emission from each process, the percentage of the biodegradability of plastic materials were calculated.

To test the biodegradability of bioplastic material in soil, it needs blank sample and reference material to compare the results of new products. In this experiment compost and cellulose was used as the blank sample and reference material for the comparison. Calculated amount of theoretical carbon released from the material and experimental cumulative amount of carbon released from the material during degradation are the main parameters of determining the percentage of biodegradation of a material.

After 45 days of aerobic degradation, Blank sample has released 116.42 g of carbon dioxide in average and cellulose containing in the compost sample (reference sample) released 152.81 g of carbon dioxide. According to the results, the percentage of biodegradation of reference material is 51.23%.

After 40 days of anaerobic digesting blank sample has released 859.1 ml of biogas and cellulose containing in compost released 988.8 ml of biogas, and after 15 days of biodegradability in anaerobic environment, the percentage is 6.8%.

According to the results, cellulose biodegradation is more efficient in the aerobic environment than anaerobic conditions when the other parameters are similar to both environments. But in both systems cellulose shows poor biodegradability due to experimental facts.

To be an acceptable biodegradability testing experiment, the reference material should degrade more than 70% after 45 days in aerobic environment and more than 70% in anaerobic environment after 15 days.

The degree of biodegradation of cellulose more than 70% in both environmental conditions can be achieved by maintaining the right conditions and well maintaining biodegradation system. Most common errors can occur during experiment are gas leakage from the composting system and not enough nutrients for the microorganisms.

If the experiment gets the expected results after the certain period in aerobic and anaerobic environment, the same system and the method can be used to measure the percentage of biodegradability of new bioplastic materials in the same conditions. It is important to follow the standard and operating procedures to obtain the accurate results from the experiment.

7 LIST OF REFERENCES

[1] Md Hafizur Rahman, Prakashbhai R. Bhoi, “An overview of non-biodegradable bioplastics,” Journal of Cleaner Production, vol. 294, 2021.

[2] “Science Matters: The Case of Plastics,” Science History Institute, [Online]. Available: https://www.sciencehistory.org/the-history-and-future-of-plastics. [Accessed 12 01 2021].

[3] Fernando, R. Lalitha S., “Solid waste management of local governments in the Western Province of Sri Lanka: An implementation analysis,” Waste Management, pp. 194-203, 2019.

[4] Jim C. Philp, Alexandre Bartsev, Rachael J. Ritchie, Marie-Ange Baucher, K. Guy, “Bioplastics science from a policy vantage point,” New Biotechnology, vol. 30, no. 6, pp. 635-646, 2013.

[5] George Bishop, David Styles, Piet N.L. Lens, “Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions,” Resources, Conservation and Recycling, vol. 168, 2021.

[6] Miriam Lettner, Josef-Peter Schöggl, Tobias Stern, “Factors influencing the market diffusion of bio-based plastics: Results of four comparative scenario analyses,” Journal of Cleaner Production, vol. 157, pp. 289-298, 2017.

[7] “Science Matters: The Case of Plastics,” Science History Institute, [Online]. Available: https://www.sciencehistory.org/science-of-plastics. [Accessed 12 01 2021].

[8] Andrew Macintosh, Amelia Simpson, Teresa Neeman, Kirilly Dickson, “Plastic bag bans: Lessons from the Australian Capital Territory,” Resources, Conservation and Recycling, vol. 154, 2020.

[9] Walter Leal Filho, Ulla Saari, Mariia Fedoruk, Arvo Iital, Harri Moora, Marija Klöga, Viktoria Voronova, “An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe,” Journal of Cleaner Production, vol. 214, pp. 550-558, 2019.

[10] “Polymers are everywhere,” University of Colorado, [Online]. Available: https://www.teachengineering.org/lessons/view/csu_polymer_lesson01. [Accessed 12 01 2021].

[11] Olivia K. Helinski, Cara J. Poor, Jordyn M. Wolfand, “Ridding our rivers of plastic: A framework for plastic pollution capture device selection,” Marine Pollution Bulletin, vol. 165, 2021.

[12] Joana Soares, Isabel Miguel, Cátia Venâncio, Isabel Lopes, Miguel Oliveira, “Public views on plastic pollution: Knowledge, perceived impacts, and pro-environmental behaviours,” Journal of Hazardous Materials, vol. 412, 2021.

[13] P.T. Harris, L. Westerveld, B. Nyberg, T. Maes, M. Macmillan-Lawler, L.R. Appelquist, “Exposure of coastal environments to river-sourced plastic pollution,” Science of The Total Environment, vol. 769, 2021.

[14] James H. Bridson, Evamaria C. Gaugler, Dawn A. Smith, Grant L. Northcott, Sally Gaw, “Leaching and extraction of additives from plastic pollution to inform environmental risk: A multidisciplinary review of analytical approaches,” Journal of Hazardous Materials, vol. 414, 2021.

[15] Joana Carlos Bezerra, Tony Robert Walker, C Andrea Clayton, Issahaku Adam, “Single-use plastic bag policies in the Southern African development community,” Environmental Challenges, vol. 3, 2021.

[16] M. Dhanshyam, Samir K. Srivastava, “Effective policy mix for plastic waste mitigation in India using System Dynamics,” Resources, Conservation and Recycling, vol. 168, 2021.

[17] Bruno Andreas Walther, Ning Yen, Chieh-Shen Hu, “Strategies, actions, and policies by Taiwan’s ENGOs, media, and government to reduce plastic use and marine plastic pollution,” Marine Policy, vol. 126, 2021.

[18] “Plastics,” European Commission, [Online]. Available: https://ec.europa.eu/environment/topics/plastics_en. [Accessed 18 01 2021].

[19] Lamprini Anagnosti, Athanasia Varvaresou, Panagoula Pavlou, Evangelia Protopapa, Vilelmine Carayanni, “Worldwide actions against plastic pollution from microbeads and microplastics in cosmetics focusing on European policies. Has the issue been handled effectively?,” Marine Pollution Bulletin, vol. 162, 2021.

[20] Caterina De Lucia, Pasquale Pazienza, “Market-based tools for a plastic waste reduction policy in agriculture: A case study in the south of Italy,” Journal of Environmental Management, vol. 250, 2019.

[21] Sibel Ügdüler, Kevin M. Van Geem, Martijn Roosen, Elisabeth I.P. Delbeke, Steven De Meester, “Challenges and opportunities of solvent-based additive extraction methods for plastic recycling,” Waste Management, vol. 104, pp. 148-182, 2020.

[22] A.E. Schwarz, T.N. Ligthart, D. Godoi Bizarro, P. De Wild, B. Vreugdenhil, T. van Harmelen, “Plastic recycling in a circular economy; determining environmental

performance through an LCA matrix model approach," Waste Management, vol. 121, pp. 331-342, 2021.

[23] S. Vinodh, M. Prasanna, N. Hari Prakash, "Integrated Fuzzy AHP–TOPSIS for selecting the best plastic recycling method: A case study," Applied Mathematical Modelling, vol. 38, no. 19-20, pp. 4662-4672, 2014.

[24] Selvaraj Geetha, Samayan Narayanamoorthy, Joseph Varghese Kureethara, Dumitru Baleanu, Daekook Kang, "The hesitant Pythagorean fuzzy ELECTRE III: An adaptable recycling method for plastic materials," Journal of Cleaner Production, vol. 291, 2021.

[25] Janis Brizga, Klaus Hubacek, Kuishuang Feng, "The Unintended Side Effects of Bioplastics: Carbon, Land, and Water Footprints," One Earth, vol. 3, no. 1, pp. 45-53, 2020.

[26] Noorul Hidayah Yusoff, Kaushik Pal, Thinakaran Narayanan, Fernando Gomes de Souza, "Recent trends on bioplastics synthesis and characterizations: Polylactic acid (PLA) incorporated with tapioca starch for packaging applications," Journal of Molecular Structure, vol. 1232, 2021.

[27] L. Srinivasa Rao, C.D. Naidu, Shuchi Tiwari, "Investigation on synthesis, structure and degradability of starch based bioplastics," Materials Today: Proceedings, 2021.

[28] Neus Escobar, Wolfgang Britz, "Metrics on the sustainability of region-specific bioplastics production, considering global land use change effects," Resources, Conservation and Recycling, vol. 167, 2021.

[29] Tetsushi Suyama, Yutaka Tokiwa, Pornpimol Ouichanpagdee, Takahiro Kanagawa, Yoichi Kamagata, "Phylogenetic Affiliation of Soil Bacteria That Degrade Aliphatic Polyesters Available Commercially as Biodegradable Plastics," Applied and environmental microbiology, vol. 64, 1999.

[30] "Bioplastics market data," European Bioplastics, [Online]. Available: https://www.european-bioplastics.org/market/. [Accessed 4 02 2021].

[31] Katrin Jõgi, Rajeev Bhat, "Valorization of food processing wastes and by-products for bioplastic production," Sustainable Chemistry and Pharmacy, vol. 18, 2020.

[32] M. Jiménez-Rosado, J.F. Rubio-Valle, V. Perez-Puyana, A. Guerrero, A. Romero, "Use of heat treatment for the development of protein-based bioplastics," Sustainable Chemistry and Pharmacy, vol. 18, 2020.

[33] N. Mozaffari, A. Kholdebarin, "A review: investigation of plastics effect on the environment, bioplastic global market share and its future perspectives," Technogenic and ecological safety, vol. 5, pp. 47-54, 2019.

[34] Nanou Peelman, Peter Ragaert, Bruno De Meulenaer, Dimitri Adons, Roos Peeters, Ludwig Cardon, Filip Van Impe, Frank Devlieghere, "Application of bioplastics for food packaging," Trends in Food Science & Technology, vol. 32, no. 2, pp. 128-141, 2013.

[35] Dobrucka, Renata, "BIOPLASTIC PACKAGING MATERIALS IN CIRCULAR ECONOMY," Scientific Journal of Logistics, vol. 15, no. 1, pp. 129-137, 2019.

[36] Kendall, Alissa, "A life cycle assessment of biopolymer production from material recovery facility residuals," Resources, Conservation and Recycling, vol. 61, pp. 69-74, 2012.

[37] Hakan Karan, Christiane Funk, Martin Grabert, Melanie Oey, Ben Hankamer, "Green Bioplastics as Part of a Circular Bioeconomy," Trends in Plant Science, vol. 24, no. 3, pp. 237-249, 2019.

[38] Piergiuseppe Morone, Valentina Elena Tartiu, Pasquale Falcone, "Assessing the potential of biowaste for bioplastics production through social network analysis," Journal of Cleaner Production, vol. 90, pp. 43-54, 2015.

[39] "Bio-based, biodegradable and compostable plastics," European Commission, [Online]. Available: https://ec.europa.eu/environment/topics/plastics/bio-based-biodegradable-and-compostable-plastics_en.

[40] Federico Battista, Nicola Frison, David Bolzonella, "Can bioplastics be treated in conventional anaerobic digesters for food waste treatment?," Environmental Technology & Innovation, vol. 22, 2021.

[41] Wu, Chin-San, "Characterization and biodegradability of polyester bioplastic-based green renewable composites from agricultural residues," Polymer Degradation and Stability, vol. 97, no. 1, pp. 64-71, 2012.

[42] Ezgi Bezirhan Arikan, Havva Duygu Ozsoy, "A Review: Investigation of Bioplastics," Journal of Civil Engineering and Architecture, vol. 9, pp. 188-192, 2015.

[43] S. Mehdi Emadian, Turgut T. Onay, Burak Demirel, "Biodegradation of bioplastics in natural environments," Waste Management, vol. 59, pp. 526-536, 2017.

[44] F. Gironi, V. Piemonte, "Bioplastics and Petroleum-based Plastics: Strengths and Weaknesses," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 33, no. 21, pp. 1949-1959, 2011.

[45] Ruggero F, Gori R, Lubello C., "Methodologies to assess biodegradation of bioplastics during aerobic composting and anaerobic digestion: A review," Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, vol. 37, no. 10, pp. 959-975, 2019.

[46] V.M. Radovenchik, M.D. Gomelya, Solid waste: collection, processing, storage, 2010.

[47] Veronika Bátori, Dan Åkesson, Akram Zamani, Mohammad J. Taherzadeh, Ilona Sárvári Horváth, "Anaerobic degradation of bioplastics: A review," Waste Management, pp. 406-413, 2018.

[48] D. Fischer, B. Glaser, Synergisms between Compost and Biochar for Sustainable Soil Amelioration, Management of Organic Waste, 2012.

[49] A.W.G. Van der Wurff, J.G . Fuchs, M. Raviv, A.J. Termorshuizen, Handbook for Composting and Compost Use in Organic Horticulture, BioGreenhouse COST Action FA, 2016.

[50] Seyedbagheri, Mir-M, "Compost: Production, Quality, and Use in Commericial Agriculture," University of Idaho Extention, 2010.

[51] F. C. M. Eddie F. Gómez, "Biodegradability of conventional and bio-based plastics and natural fiber composites during composting, anaerobic digestion and long-term soil incubation," Polymer Degradation and Stability, pp. 2583-2591, 2013.

[52] Federica Ruggero, Riccardo Gori, and Claudio Lubello, "Methodologies to assess biodegradation of bioplastics during aerobic composting and anaerobic digestion: A review," Waste Management & Research, pp. 959-975, 2019.

[53] Bartleson, Becca, "Purpose of Titration," 24 04 2017. [Online]. Available: https://sciencing.com/purpose-titration-5406434.html.

[54] Estonian centre for standardisation, "Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions," ISO 14855-1: 2012, 2012.

[55] European committee for standardization, "Determination of the ultimate anaerobic biodegradation under high-solids anaerobic-digestion conditions," ISO 15985: 2014, 2014.

[56] R. Mohee, G. Unmar, "Determining biodegradability of plastic materials under controlled and natural composting environments," Waste Management, vol. 27, no. 11, pp. 1486-1493, 2007.

[57] Guo W, Tao J, Yang C, Song C, Geng W, "Introduction of Environmentally Degradable Parameters to Evaluate the Biodegradability of Biodegradable Polymers," PLOS ONE, vol. 7, no. 5, 2012.