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**THE ROLE OF BIO-BASED POLYESTERS IN FOOD AND LIQUID PACKAGING**

Examiners: Professor Kaj Backfolk  
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## **ABSTRACT**

Lappeenranta University of Technology  
Faculty of Technology  
Master's Degree Programme in Packaging Technology

Okwuejunti Emeka

## **THE ROLE OF BIO-BASED POLYESTERS IN FOOD AND LIQUID PACKAGING**

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Packaging industries from both in recent past and today have since depended on the usage of plastic derived from petroleum in the production of packaging solutions for food and liquid. Basically, with these increased and increasing demands, a sustainable society with the avoidance of carbon emissions, waste, landfills, greenhouse gas cannot be guaranteed with the usage of petroleum-derived plastics. More than ever the populace and the World at large are not only seeking for efficient and effective packaging solutions but are also in lookout for packaging solutions which are sustainable both in shelf life and environment wise. This thesis work focuses on evaluating and analysing the roles of bio-based polyesters in food and liquid packaging as it aligns with the arising pressing need required in the industry and the world at large. Furthermore, this thesis also focuses on identifying the potential role of joint developments and acquisition present in the industry. Based on the evaluation and market analysis carried out, it was discovered that bio-based polyesters when used in packaging helps in reducing emission of CO<sub>2</sub>, dependability on fossil fuel usage, carbon footprint of packaging, greenhouse gases, offers more recycling and recovery options, and sustenance of a good ecosystem are few out of numerous reasons why bio-based polyesters are perceived and projected to dominate packaging industries in nearest years to come.

Nevertheless, bio-based packaging has experienced a setback in competitiveness of price when compared to conventional packaging solutions as a result of cost incurred in research and development, fall in price of crude oil and cost incurred in total production. However, all these can be better overcome with appropriate implementation of policies that will aid the growth of bio-based polyester usage by the government, improvements in mechanical and barrier properties and couple with the synergy experienced in development and commercialization of Polyethylene-furanoate (PEF), which is 100% recyclable and renewable, so a significant breakthrough is optimistic for bio-based polyesters in the nearest future.

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Lappeenranta, Finland

13<sup>th</sup>, March 2018

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## LIST OF SYMBOLS AND ABBREVIATIONS

BAU	Business as usual
BBI	Bio-based Industries
BDO	Butanediol
Bio-PET	Biopolyethylene terephthalate
Bio-PTA	Purified Terephthalic Acid
CA	Cellulose acetate
EFSA	European Food Safety Authority
EG	Ethylene glycol
EU	European Union
EuBP	European bio-plastics
FDCA	Furandicarboxylic acid
FDME	Furan Dicarboxylic Methyl Ester
HDPE	High-density polyethylene
HMF	Hydroxymethylfurfura
LDPE	Low-density polyethylene
MSW	Municipal solid-waste
OECD	Organization for Economic Co-operation and Development
PBS	Poly (Butylene succinate)
PCL	Polycaprolactone
PE	Polyethylene
PEF	Polyester-furanoate
PET	Polyethylene-terephthalate
PHA	Polyhydroxy-alkanoate
PHB	Polyhydroxybutyrate
PLA	Poly (Lactic acid)
PP	Polypropylene
PS	Polystyrene
PTF	Polytrimethylene furandicarboxylate

PUR	polyurethanes
PVA	Polyvinyl alcohol
PVC	Polyvinylchloride
R-PET	Recycled polyethylene terephthalate
ROP	Ring opening polymerization
SDGs	Sustainable Development Goals
SWOT	Strengths, Weakness, Opportunities, threats
TPA	Terephthalic acid
TPS	Thermoplastic Starch

# 1 INTRODUCTION

With the exception of paper-based products, the production of bio-based polymers is currently attracting a great deal of attention, as a result of the price fluctuation and future depletion of crude oil reserves, coupled with demands for environmentally sustainable products. They are being regarded as major component of or modern world and have a wide range of application in varieties of field. However, many of this polymers used in packaging have enormous environmental impact, and can span from a decade to hundreds of years to decompose and breakdown. As much as 60% of post-consumer plastics waste are produced by diverse households that often are single use packaging [1]. Environmental impact of polymers is extremely much, statistics from Worldwide shows that 43% of Marine mammal species, 44% of seabird species and 86% of sea turtle species are vulnerable to ingesting plastics debris in marine [2]. The environmental effect experienced is far more than the death of these animals but the major concern is the release of these polymers back into their natural ecosystem [3]. Problem encountered from the usage of this polymers as there is a high waste management cost and years after years an approximate of 140 million tons of synthetic polymers are produced with an estimate 20-25% of which ends up in municipal landfills [4]. If proper environmental regulation is to be maintained during the cause of collecting and managing landfills the cost will be extremely outrageous and can affect the budget of many municipals. Essentially, it is imperative to put into consideration that packaging revolves around these 3 concepts i.e. Environmental, Economic and Social, which cover all aspects of sustainability. Recent trend in EU packaging market shows a budding interest towards “Green” packaging, which means using recyclable materials, reduced material usage, recycled materials, and polymers extracted from biomass. The evolution of eco-friendly packaging solutions in EU is as a result of EU directives. However, major threat this evolution poses is cost, as the economics associated with transporting and processing the recycled material is more than the new polymer based products [5].

## 1.1 Background

Defining Bio-Polyester in part, “Bio” originates from the Greek word “bios” indicating “human life”. However, in the packaging, polymer and composite disciplines, there happens to be numerous definitions used, and misconceptions are very typical. The prefix “bio” is sometimes used for biodegradable materials or materials from renewable resources [5]. “Polyester” on other hand means a synthetic resin in which the polymer units, used mainly to make synthetic textile fibers are linked by ester groups. Polyester is a category of polymers that is made up of the ester functional group in their main chain. Specifically, it is generally referred to a type called polyethylene terephthalate (PET). Polyesters as a whole include naturally occurring chemicals, such as in the cutin of plant cuticles, also as synthetics via step-growth polymerization such as polybutyrate. Therefore, bio-based polyesters is a microbial polyester biosynthesized from sugar and plant oil by microorganism, and some bio-polyesters, such as Bio-PE and Bio-PET are non-biodegradable in nature, it can also be defined as materials that are being derived, directly or indirectly from a renewable source of living matter [6]. .

Biodegradation can be defined as a chemical process in which microorganisms such as bacteria, fungi and other biological elements feed on a substance as a food source so that its original form disintegrates and it is completely converted into water, CO<sub>2</sub> and biomass. Under specific conditions of moisture, temperature and O<sub>2</sub> availability, biodegradation is a relatively rapid process. In landfills the degradation of even highly biodegradable materials takes place gradually. Biodegradability has no practical meaning unless certain factors, such as the environment, timeframe and context are specified [5].

Even though bio-based polyesters used as packaging materials may be biodegradable and non-biodegradable in nature, this is not the main driving force behind their development. Rather, it is driven by the motivation to switch to renewable resources, thereby resulting to a more environmentally friendly packaging. Today’s synthetic polyesters are mostly produced from petroleum distillates, which are not biodegradable, a good example of a bio-based, but not biodegradable plastic is the new plant bottle (Bio-based drop in PET) from the Coca-Cola Company. Persistent polyesters lead to significant sources of environmental degradation, having adverse effect on wildlife when they are discharge in nature. On a global production scale, approximately 7% of petroleum produced is utilized for the production of plastics [7]. Hence,

today's deliberation on renewable energy is having a positive impact on the plastics industry. The setbacks are notable and literally the driving force that influence the energy controversy. Specifically fossil fuels, such as petroleum and gas, are of limited reserve and have fluctuation in prices. Another challenge confronting the legislative is the immediate rising political instability concerning the increasing use of plastics and its environmental impacts. [8].

The usage of bio-based material in food packaging is increasingly gaining ground and reasons best attributed to the advantages it poses over fossil-based plastics which are made from non-renewable resources. Bio-based materials use renewable resources in their production and as a result may be biodegradable or compostable in nature depending on their molecular structures. Consequently, this material when used offers a better means of disposal as they are biodegradable and hence reduces disposal to landfill. With the continuous rate at which public interest and environmental concerns arises about non-renewable resources and the amount of waste being sent to landfill. However, the use of materials derived from biomass is desirable based on its advantages, but also it is pertinent to ensure that the food packaged within it, is not compromised. Recently, bio-based industries have experienced increased usage in food contact application since continuous development has been unending. Nevertheless, all materials being used must comply with Framework Regulation (EC) N0 1935/2004, i.e. they should not transfer their constituents to food in quantities which could endanger human health, bring about an unacceptable change in the composition of the food or bring about a deterioration in the organoleptic characteristics. This has positioned the packaging industry into considerable regulation and public pressure, but fair enough there is a prospective alternative or replacement for packaging which are fossil-based to those made from renewable and natural sources. [9]

Currently, the predominate challenge confronting the food industry in the production of bio-based polyester packaging is to equal the durability of the packaging with product shelf life. Significant factors responsible for most food deterioration under specific conditions include relative humidity, environmental temperature, ultraviolet light, bacterial activity, etc. In order to meet up with projected industrial-scale output in terms of application, special procedures must be adhered to in the preparation of bio-based polyester material so as to address theses aforementioned common factors associated with food degradation. Additionally, petroleum resources availability is finite and is dwindling. Thus, it will be of paramount importance to find

dependable plastic replacement, such as in disposable and reusable packages. The incessantly growing public uncertainty on this predicament has prompted research work in bio-based polyesters as alternatives to traditional non-degradable polyesters. e.g, polyethylene and polystyrene [10].

## **1.2 Objective**

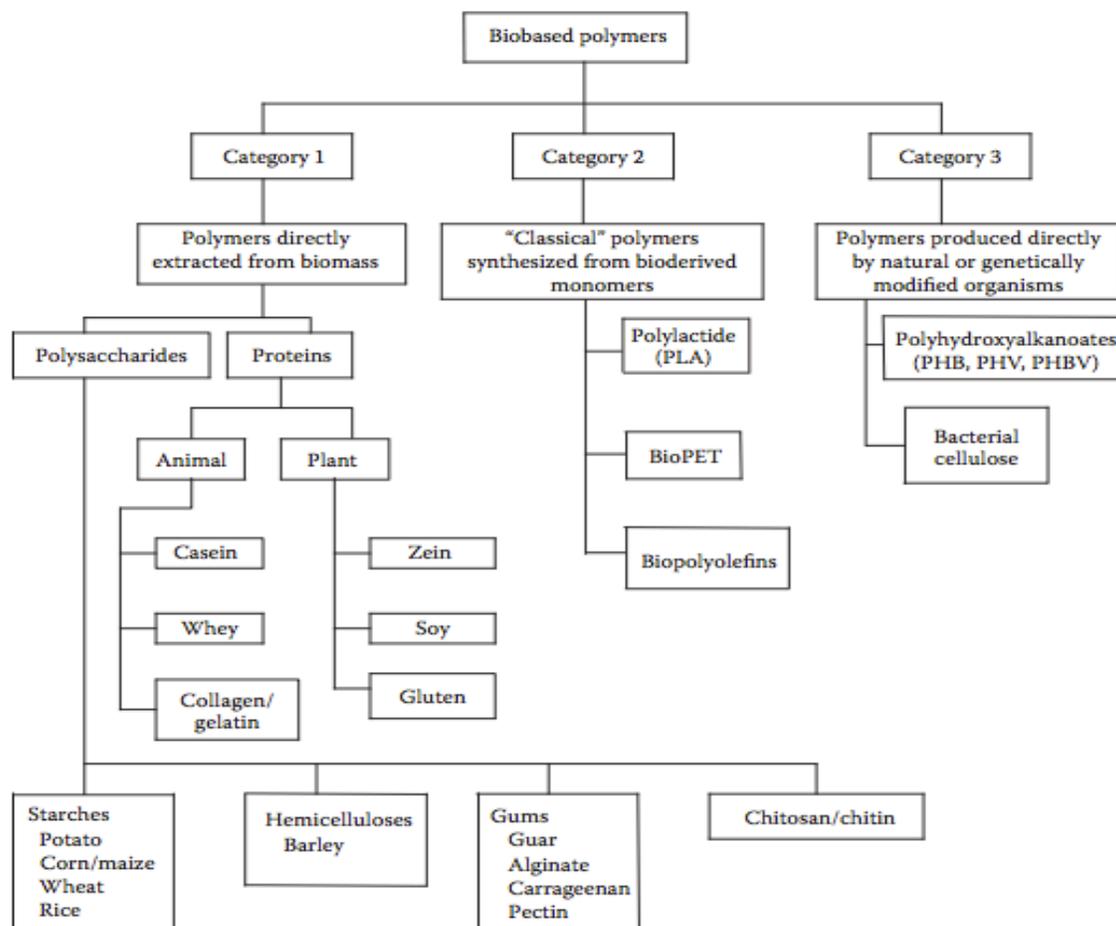
The objectives of this master's thesis are as follows;

1. To understand the use of bio-based polyesters in food and liquid packaging.
2. To identify joint development present in this industry.
3. To identify current active players in the industry.
4. Explain the production process of various bio-based polyesters.
5. To identify why bio- based polyester has low penetration in the market.
6. Make recommendations on how this can be solved.

## **1.3 Classification**

Generally, bio-based packaging materials can be classified based on their chemical composition, origin, synthesis method and economic importance. Bio-based polymers can be divided into three broad categories as depicted in figure 1 [6]:

1. Polymers directly extracted from biomass such as starch, cellulose and chitin
2. Polymers produced by chemical synthesis using bio-based monomers as polylactic acid (PLA) and biopolyethylene terephthalate (Bio-PET)
3. Polymers produced by micro-organisms or bacteria such as the polyhydroxyalkanoates (PHA)



**Figure 1.** Schematic illustration of Bio-based polymers based on their origin and method of production [5].

### 1.3.1 Polymers Extracted from Biomass

Polymers derived from biomass are typically available polymers i.e. from agricultural animals, marine and plants. Examples include polysaccharides in the form of starch, chitin and cellulose and proteins such as collagen, whey, casein and soy. Majority of these polymers are categorized differently by their affinity for water and nature and to some extent based on crystalline-factors generating processing and performance issues, especially for packaging of moist products. Conversely, polymers in this category possess outstanding gas barriers [6].

### **1.3.2 Polymers Produced by Chemical Synthesis Using Bio-Based Monomers**

The most common bio-based plastic synthesized from bio-based monomer is poly (lactic acid). Polylactic acid is classified under the class of polymer that has shown the highest potential in terms of large-scale commercial production among renewable packaging materials. The production of polymers using chemical synthesis offers a whole new broad approach of attainable “bio-polyester”. Bio-based sources for the synthesis of bio-based can as well be obtained from monomers of different conventionally fossil-based polymers versions of the plastics [11].

### **1.3.3 Polymers by microbial production**

The production process of these polymers is either by genetically modified bacteria or microorganisms; also polyhydroxyalkanoates are classified under this category of bio-based polymers. Microbial process has been applied to produce cellulose, such as *nata de coco*, which is produced by the fermentation of coconut water in the presence of a bacterial called *Acetobacter*. However, bacterial cellulose is yet to be commercialized due to high cost of production [12].

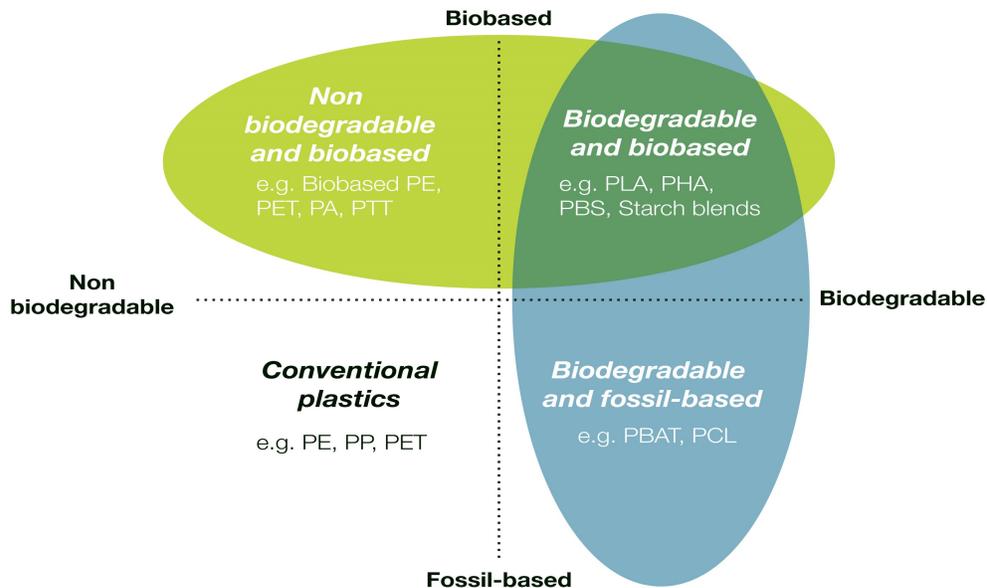
## **1.4 Bioplastics**

Bio-plastics according to the European bioplastics are plastics made from renewable biomass resources such as corn, potatoes, sugarcane, algae, etc. Bioplastics are fully or partially bio-based, and/or biodegradable or compostable.

Three main groups of bioplastics by material types

1. Bio-based or partially bio-based, non-biodegradable plastics, e.g. bio-based PE, PP, or PET (also known as drop-ins) and bio-based technical performance polymers such as PTT or TPC-ET;
2. Plastics that are both bio-based and biodegradable, e.g. PLA and PHA or PBS;

3. Plastics that are based on fossil resources and are biodegradable, e.g. PBAT [5].



**Figure 2.** Types of bioplastic (Biodegradable and non biodegradable) [5].

Figure 2 shows the arrangement of common types of bioplastics in accordance to their biodegradability and bio-based composition.

## 1.5 Methodology

This research work will concentrate on explaining the method of producing various bio-based polyester as well as identifying the key players in the industry. The work will also investigate the reasons bio-based packaging is fairly undeveloped polyesters, low penetration in the industry and possible solutions will be determined on the basis of the market analysis of bio-based packaging such as market projection and current demand of bio-based packaging with the application of SWOT analysis technique.

The data for the thesis was collected from various sources i.e. scientific journals, books, and other relevant sources including Google Scholar, Wikipedia and library database from Lappeenranta university of Technology.

## **2 LITERATURE REVIEW**

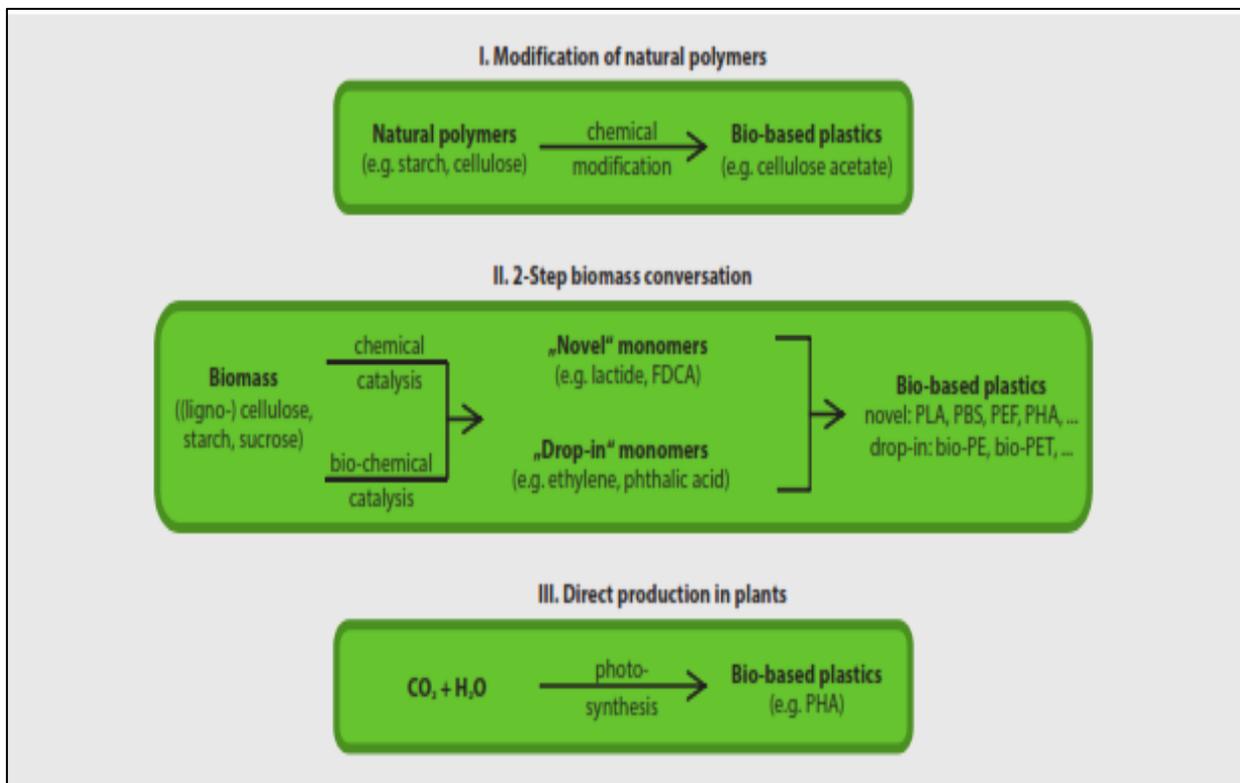
Food and liquid packaging play a significant role in preserving food all through the distribution chain. Basically, without appropriate packaging the processing of food can become susceptible to contamination by direct contact with physical, chemical and biological foreign matters [13]. As a result, packaging is an essential phase in food production as it is very imperative and of utmost priority. During the last ten years, the packaging industry a whole has developed technologically into a tremendously improved service provider, most especially for perishable foods; the industry has exploited the leading edge in manufacturing and process engineering, material science along with the continuous improvement in food science sector [14,15].

### **2.1 Bio-based polymer as a packaging material**

Bio-based materials are becoming a commonly used alternative for food and liquid packaging, one of the major reason is because bio-based materials are produced with renewable resources which makes it a better choice of packaging material when compared to fossil-based plastics. Furthermore, assessing bio-based materials from the biodegradability and compostability point of view, the end product offers a better alternative to disposal in landfill as a result of natural biopolymer susceptibility to microorganisms, which leads to biodegradability due to the reason that bio-based materials derived from naturally occurring polymers are biodegradable. As a matter of fact, public concern and interest relating to environmental degradation involving the utilization of non-renewable resources and the huge quantity of waste being generated and discharged to landfill accumulates and it has been envisaged that this particular trend will persist and escalate. Even though it is well acknowledged that the use of resources obtained from biomass is environmental friendly and policy regarding quality of the food packaging is not in any means compromised. The use of petroleum-derived materials will increasingly lead to enhance emission of greenhouse gases and subsequently generate substantial amount of waste. The continuous development of bio-based as an alternative would provide social, economic and environmental benefits to the planet and mankind if they successfully have good market penetration [16].

### 2.1.1 Production of bio-based polymers

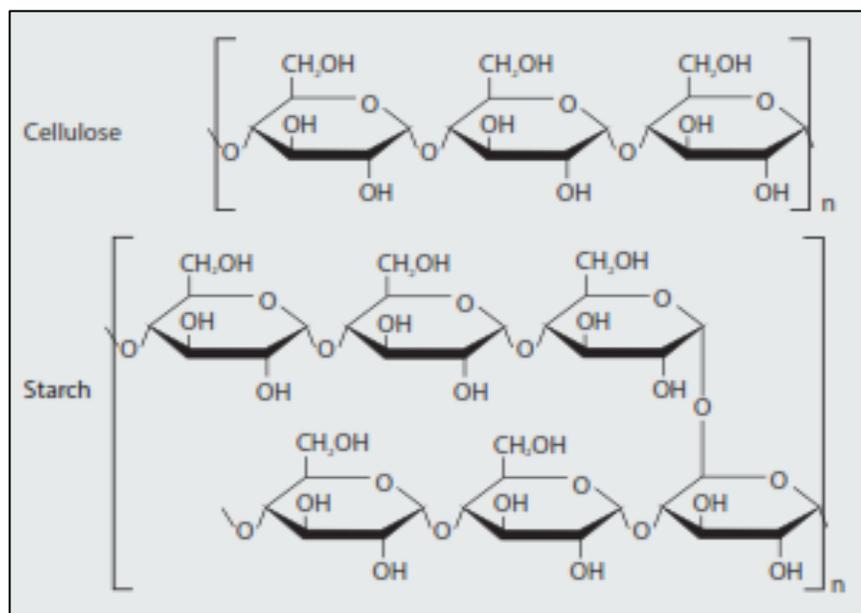
Basically, the production of bio-based polymers to yield bio-based plastics entails three fundamental steps. The first step involves the conversion of natural polymers to bio-based plastics through a process of chemical modification, while ensuring that the polymer root is unchanged. In the second step, which is sub-divided into biomass conversion process, whereby bio-based precursors (monomers) are produced by catalytic biochemical and/ or chemical transformation reaction and the monomers, thereafter undergo the process of polymerization. The third step is a direct production from plant, making use of photosynthesis to produce polymeric material that has the characteristics of a plastic without requiring additional modification [8].



**Figure 3.** Production routes of Bio-based Polymers [8].

### 2.1.2 Plastics derived from natural polymers

Many common industrial applications use natural polymer. In order of their annually production volume, topping the list are cellulose, chitin, and lignin. Currently, lignin and chitin utilization as filler for rubber and thermoplastics are being thoroughly studied [17,18,19,20,21].



**Figure 4.** Structure of cellulose and starch [8].

Among the different types natural polymers, the most commonly utilized ones for industrial production of bio-based polymers are starch and cellulose. Figure 3 depicts their production step, which is in compliance with route 1, and their monomeric building blocks are very identical to the illustration in Figure 4, they have differing properties. Starch and cellulose have to be modified before they can be processed as a thermoplastic material.

## **Starch**

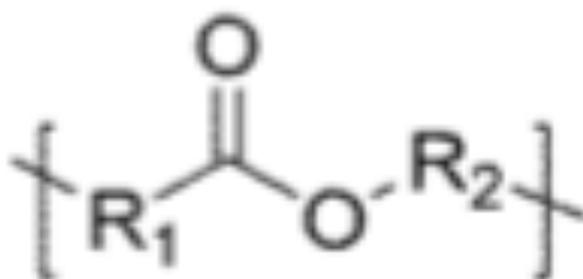
The major source of storage for carbohydrate in green plants is known as starch. Starch is polysaccharide which can be found in tubers, seeds, fruits, stem, leaves and roots, and it has a semi-crystalline structure because it undergoes a process known as thermal degradation before it attains its melting point. Although, thermoplastic processing cannot be applied to native starch, and the term “thermoplastic Starch” is used to address any bio-based plastic that comprises of starch. This can be produced from starch granules and it is done by mixing and heating them together with plasticizers such as water and glycerol, in a chemical process known as destructurization. These granules exhibit strong inter-molecular property as a result of the hydrogen bonding that exists between hydroxyl groups on the granule surface and are hydrophilic in nature. Some of the raw materials in which starch can be obtained from are potatoes, wheat, tapioca, rice and corn. Starch plastics are largely used in packaging applications such as films or bags, soluble films and loose fill materials. Also, food packaging application such as wrap films, boxes and tableware and single-use foamed trays are made from starch blends. A good advantage they have is their relative high water permeability that is convenience for fog-free packaging of warm foods [22].

## **Cellulose**

Cellulose is more stable than starch because of its high degree of crystallinity which makes them degrade prior to melting. It is the most abundant natural polymer on earth and is the main cell constituent on all major plants. Although, cellulose is present in plants, nevertheless it is abundantly more in cotton fibers, linen fibers, hemp and wood pulp. Cellulose is difficult to use since it is hydrophilic in nature, has crystalline structure and it is insoluble but cellulose, but its price is fascinating. In making cellophane or cellulose film, it requires the dissolving of cellulose in a mixture of carbon disulphide and sodium hydroxide which is then after recast into sulphuric acid. Alternatively, cellulose can be dissolved directly using loncell-F process, whereby the number of procedures applied in viscose process are eliminated [23].

## 2.2 Bio-based polyesters

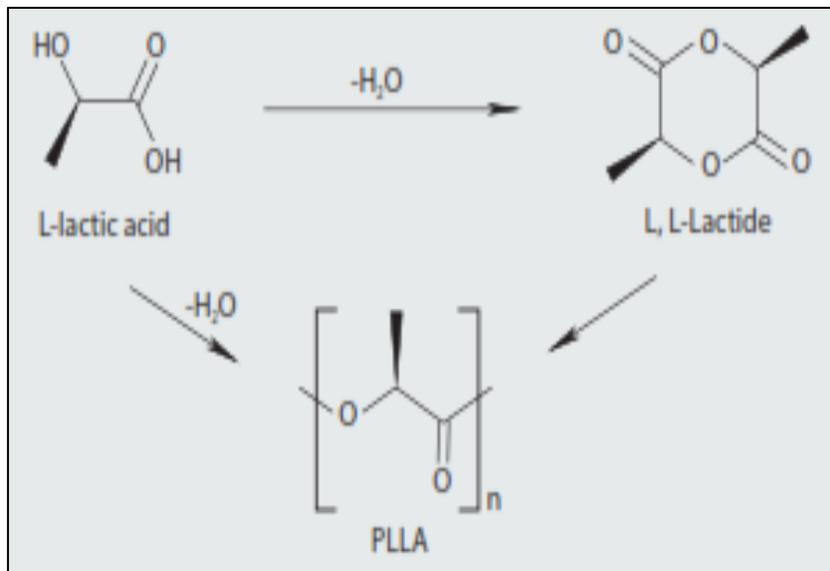
Polyesters can be classified among polymeric materials group based on their functionalities and structures, whereby the main chain is made up aliphatic or aromatic moieties  $R_1$  and  $R_2$  bonded together by ester groups. Basically, polyesters are formed from the polymerization of hydroxyl acid [24].



**Figure 5.** Structural formula of polyesters [24]

### 2.2.1 Poly (lactic acid)

Poly(lactic acid) monomers are produced by fermentation of carbohydrate feedstock and are characteristically amorphous or semi-crystalline polyesters. Agricultural products such as maize, wheat or agricultural waste such as molasses, whey, green juice etc. may be the carbohydrate feedstock. PLA can be produced through a process known as direct condensation of LA or via ring opening polymerization (ROP). ROP synthetic method produces higher molecular weight of PLA with selected catalysts [17].

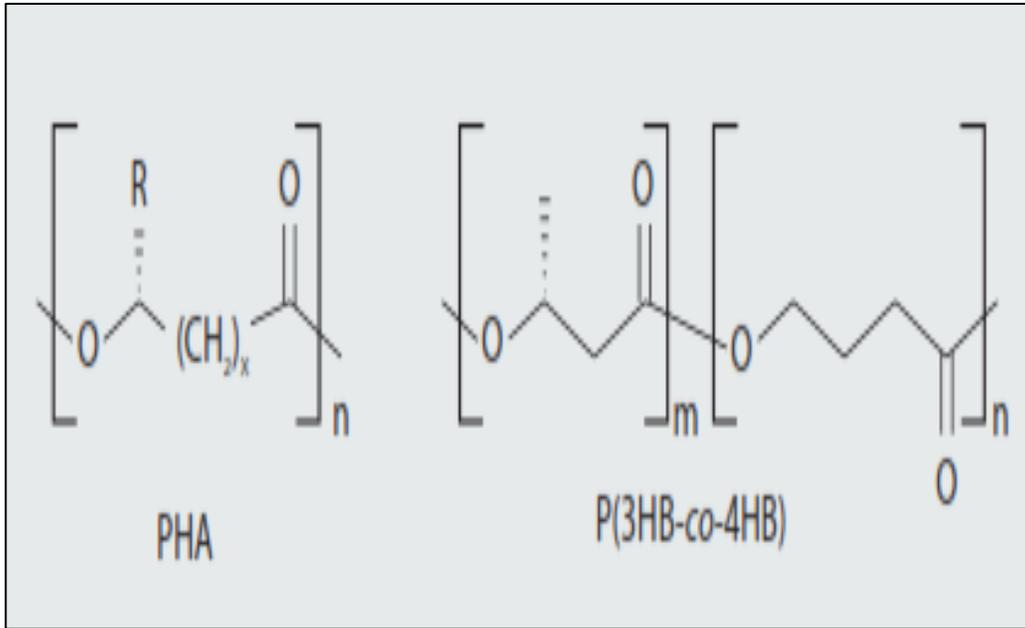


**Figure 6.** Synthesis of Lactide and Poly (Lactic acid) [17]

The figure above shows the products of both routes based on the generally adopted and specified nomenclature, which are known as poly (lactic acid), made from poly condensation products of LA and polylactides, prepared by ROP of lactides. PLA is classified under the category of synthetic polymers that are completely biodegradable and compostable [17].

### 2.2.2 Poly (hydroxyalkanoate)

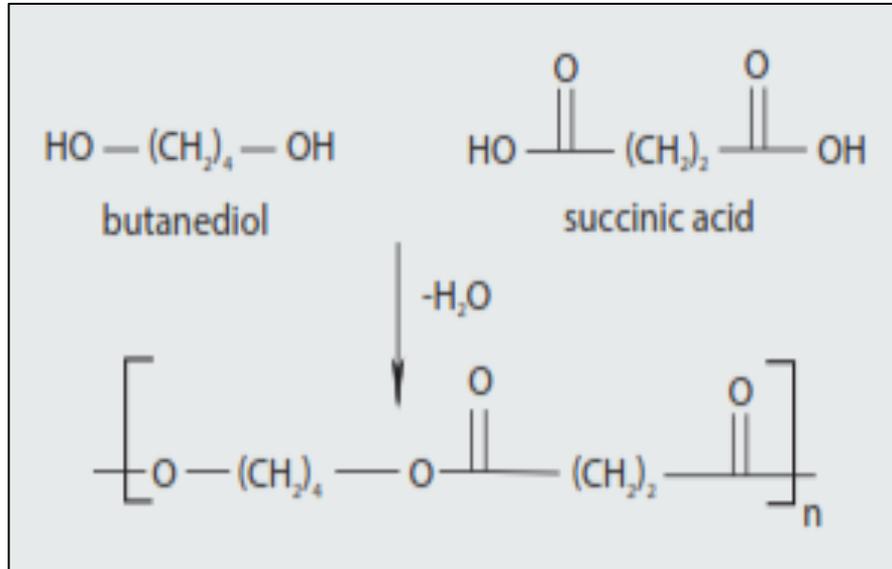
PHA belongs to a category of polyesters, that are known to be amorphous or semi crystalline and completely biodegradable. It can be prepared from of renewable feedstock by bacteria fermentation or in genetically processed plants. Producing PHA using microorganisms involves three basic steps. The fermentation step uses a fed batch process which is in two stages, thereafter the solvent-based extraction precipitation stage comes next, and after drying, the resulted PHA plastic in its purified form is ready. The molecular structure and composition of PHA play a vital role in the determination of their properties. PHA is used for packaging (bags, boxes and foams) [17].



**Figure 7.** Poly (hydroxyalkanoate) left: genetic structure; right: PHA-copolymer [17].

### 2.2.3 Poly (butylene succinate)

This is a fully biodegradable and semi crystalline polyester, typically produced from polycondensation of succinic acid and 1, 4-butanediol (BDO) [26]. PBS is identified as white thermoplastic aliphatic polyester and a high melting point above 100°C with a low glass transition temperature (T<sub>g</sub>) ranging between -45 and -10°C, it possesses a remarkable mechanical properties, comparable to the likes of PE and PP. PBS is usually mixed with other thermoplastics such as TPS or PLA, or comonomers like terephthalic acid or adipic acid in order to adjust these properties [27].

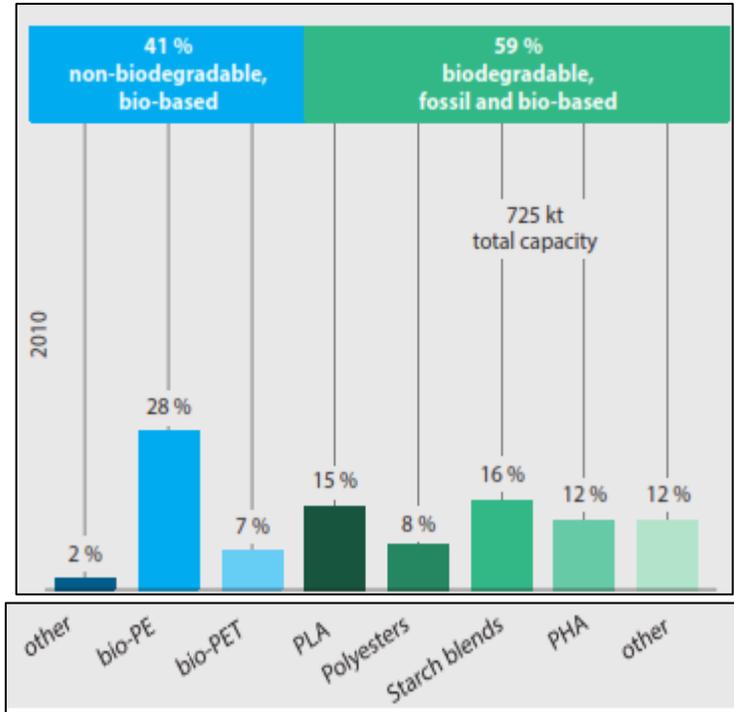


**Figure 8.** Synthesis of Poly (Butylene succinate) [27].

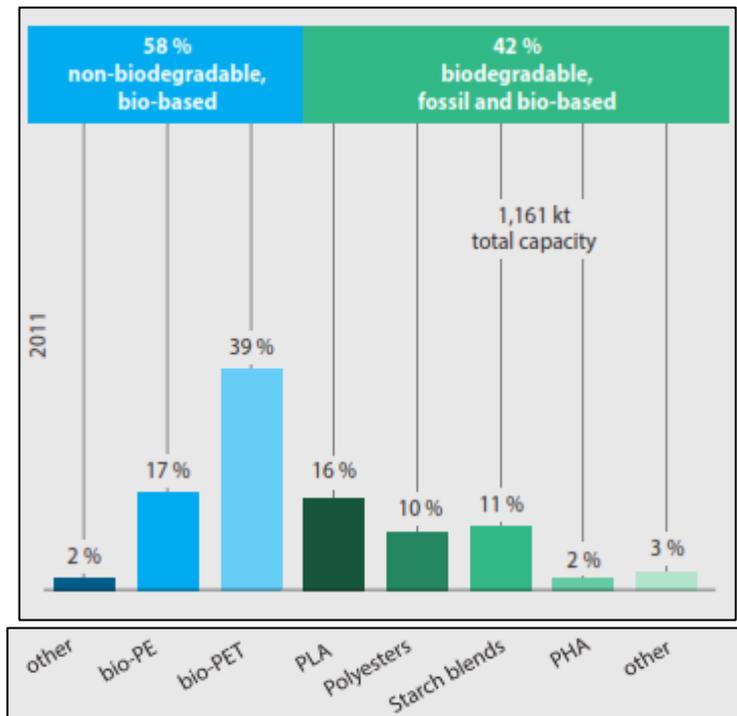
Several methods have been developed on how to process PBS, including the fermentation of carbohydrates making use of different types of bacteria and fungi. Alternatively, fermentation of sugar could be used as a direct approach to bio-based BDO, making use of genetically modified microbes. The production of Poly (Butylene succinate) is from fossil resources. Moreover, the bio-based composition is projected to be on the rise, since the production capacities of the constituent bio-based monomers as announced have attracted joint collaboration from companies such as Bioamber, Myriant, Reverdia, CSM Purac, BASF and Genomatica [28].

### 2.3 Bio-based conventional plastics

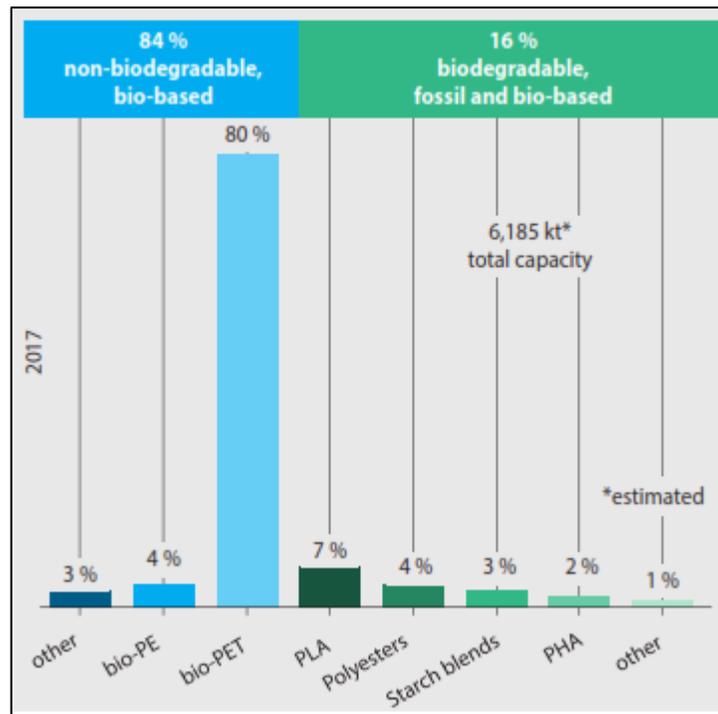
The major focus bio-plastic has been on applications that involved biodegradability, and production capacities have remained comparatively low for durable bio-based plastics. Since 2011, Bio-PET has been the most widely sought after bio-based non-degradable plastic, which is foreseen to increase at a remarkably high rate. Reason best attributed to the great demand for sustainability as shown in figures 9-11.



**Figure 9.** Global production capacity of bio-plastic in 2010 [8].



**Figure 10.** Global production capacity of bio-plastic in 2011 [8].



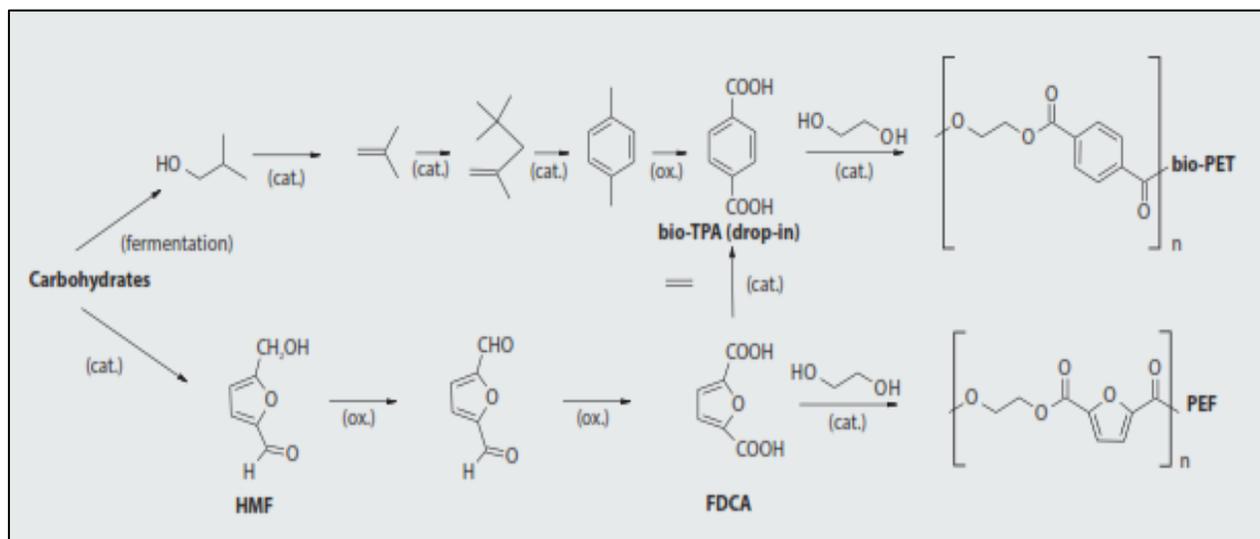
**Figure 11.** Global production capacity of bio-plastic by 2017 [8].

According to recent market survey, the plastic industry has responded to the increased in demand by altering the production in favour of bio-based non-biogradable plastics. The projected swift grow of the overall production capacities to about 6.185 ktpa by 2017 is expected as depicted in Figure 11, which illustrates the change in preference of the predominant sector from biodegradable plastics occupying 59 percent in 2010 to non-biodegradable, bio-based plastics with 84% by 2017 [8].

### 2.3.1 Bio-based (ethylene terephthalate)

Thermoplastic Polyester popularly known as PET is produced through poly-condensation of ethylene glycol (EG) and terephthalic acid (TPA). PET areas of usage are in fiber (textiles) and packaging applications such as bottles and food containers. The production of PET divided into two phases, esterification of TPA with EG is the first phase while the second phase is poly-

condensation. In the second phase PET is formed through a transesterification reaction [29]. Bio-based PET production capacity in 2011 reached 620kt, a 12-fold capacity increase when compared with 2010 bio-PET production capacity (Figure 9, 10 & 11). No doubt the increase in Plant-Bottle was massive and in 2009, Coca-Cola launched beverage bottles made from it. Other manufacturers have also joined the usage of Plant-Bottle for food and beverage companies. Bio-PET production capacity is forecasted to attain 5000ktpa by 2016 due to Coca-Cola's intention to switch fully to bio-based bottle by 2020 (European Bio-plastics, Institute for Bio-plastics and Bio-composites, 2012; nova-institute GmbH, 2013) [30]. This commitment prompted the development of Poly (ethylenefuranoate) (PEF), which is structurally identical to PET and its production involves the catalytic process between ethylene glycol and 2,5-furandicarboxylic acid (FDCA). Renewable resources are used in the production of FDCA, Figure 12 shows the process. Firstly, carbohydrates are converted to hydroxymethylfurfural (HMF) and the adjacent catalytic oxidations yield FDCA [31]. Lastly, the classical polyesterification of FDCA and EG gives PEF.



**Figure 12.** Breakdown of sugar to Bio-PET and PEF [32].

However, PET and PEF compete in performance evaluation, but regarding certain factors such as the oxygen, carbon dioxide and water barrier properties PEF surpasses PET, which could possibly minimize foods spoilage due to better prolonged shelf life [33].

### **2.3.2 Polyethylene furanoate (PEF)**

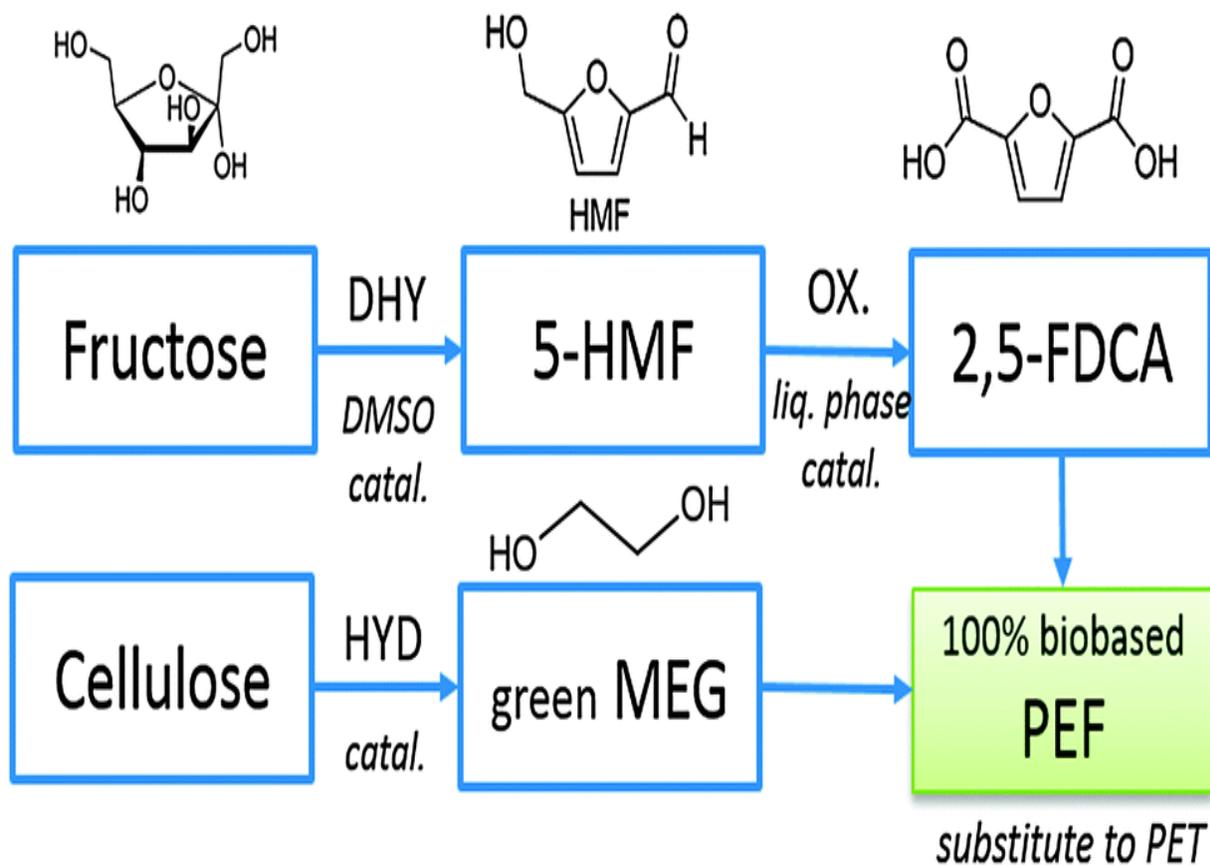
In an effort to enhance sustainability, Avantium and The Coca-Cola Company enter into a partnership agreement to develop next generation 100% Plant Based Plastic. PEF is a 100 % bio-based polymer produced from plants having a high potential to substitute the plastic industry's widely used polyethylene terephthalate (PET), which is a durable material derived from conventional resources [34].

PEF is a novel polymer that has the potential to oust PET. In respect to Avantium press release, PEF possesses remarkable properties such as lower permeability of oxygen, carbon dioxide and water and the ability to withstand heat. The company claims that it can be used in plastic bottling, disposables, filters, flexible packaging, trays or cups, and industrial fibers [32].

### **2.3.3 Synthesis reaction for PEF**

Catalytic process is utilized to obtain Furan-dicarboxylic acid (FDCA) from sugars in a 2-step chemical scheme as illustrated in figure 13. Avantium uses FDCA in the production of the polyester, which is Polyethylene-furanoate (PEF), a 100% bio-based polymer that has the potential to possibly serve as an alternative to Polyethylene-terephthalate (PET) in global markets.

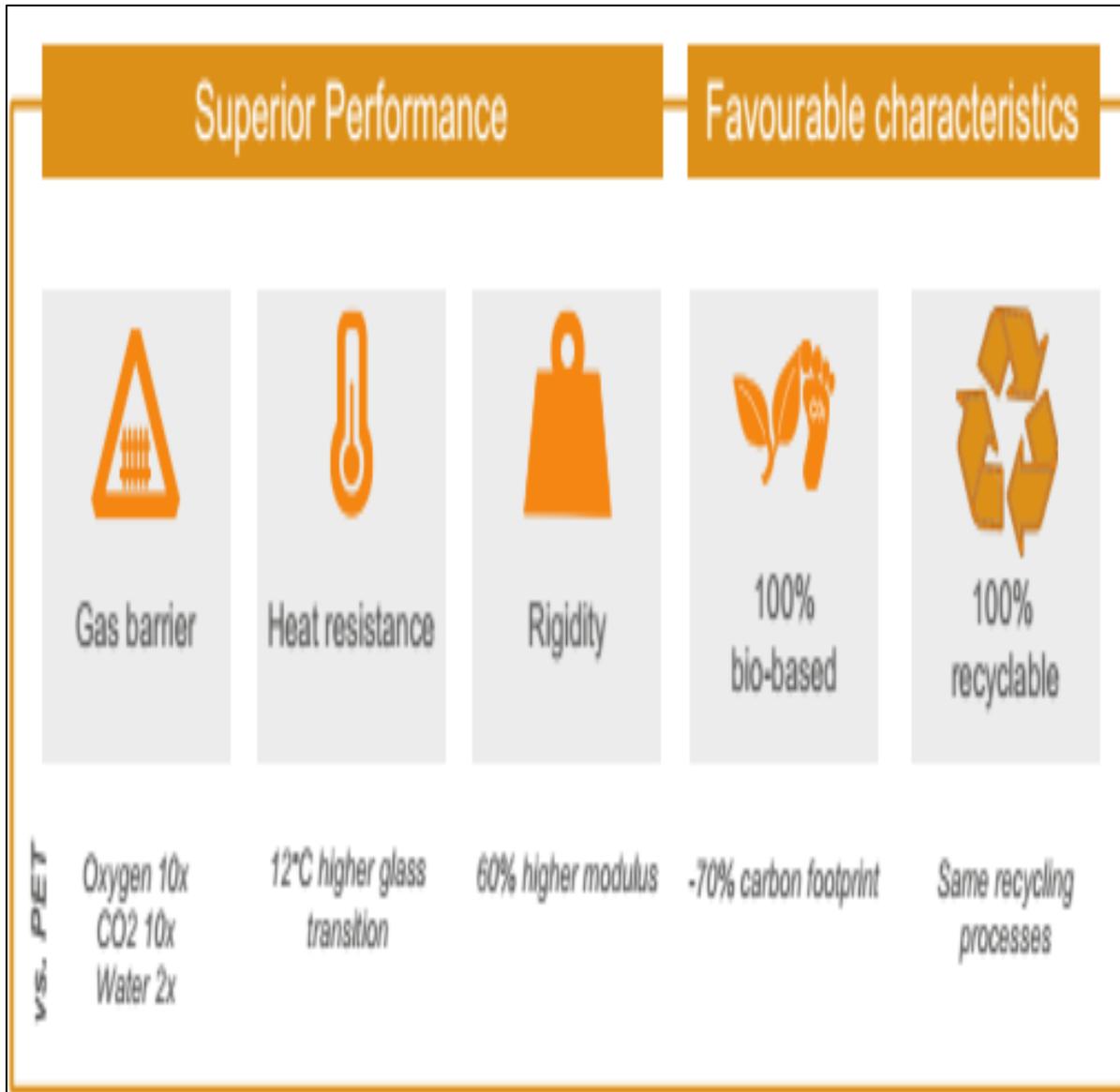
PEF can be termed as the next generation polyester, known for its better mechanical and barrier properties than the current top selling polyester (PET). Moreover, the recycling of PEF can be done alongside with PET at the same recycling line at about 5% PEF with no direct effect on the PET performance [32].



**Figure 13.**Block-diagram for the production of 100% bio-based PEF [32].

### 2.3.4 Bio-PEF versus Bio-PET

PEF which possess 6-10 times better barrier for oxygen when compare to PET figure 14, and three times for carbon dioxide, all assessments for PEF are satisfactory, not merely against PET but also against all other possible competing packaging materials. PEF has a good process adaptability since it can be processed both in the same machinery as PET; the bottle producers do not need new equipment for the replacement of PET with PEF.

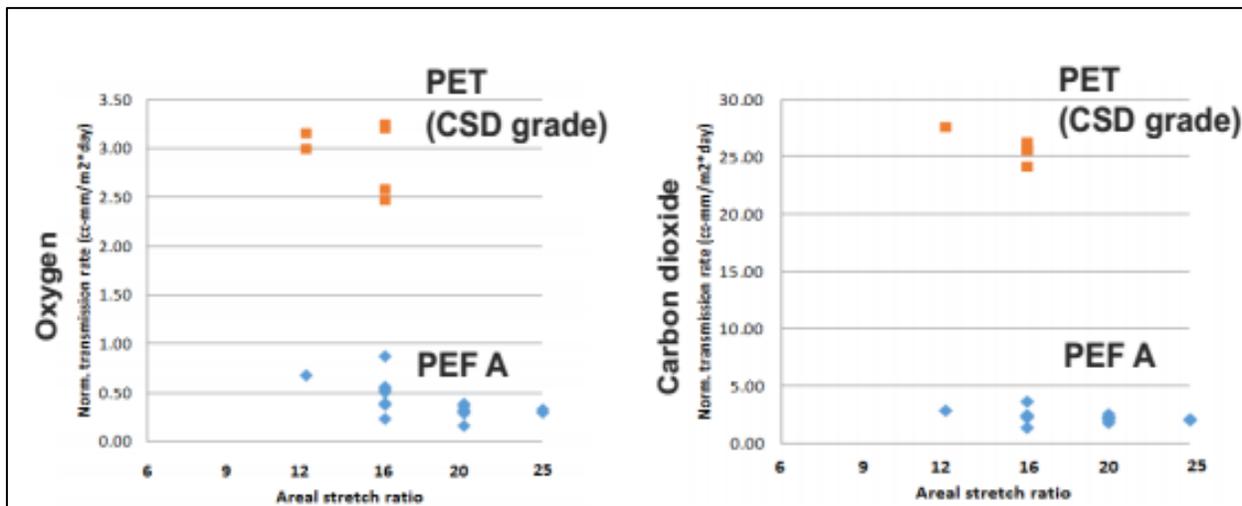


**Figure 14.**PEF versus PET [35].

In addition, PEF has a lower melting temperature and higher glass transition temperature, which makes it easier to handle and use as shown in table 1. Finally, in large quantities it is even more economical when compared to Bio-PET.

**Table 1.** Differentiating between the properties of PET and PEF [35].

Property	PET	PEF
Density	1.36 g/cm <sup>3</sup>	1.43 g/cm <sup>3</sup>
O <sub>2</sub> permeability	0.114 barrer <sup>1</sup>	0.0107 barrer <sup>1</sup>
CO <sub>2</sub> permeability	0.46 barrer <sup>1</sup>	0.026 barrer <sup>1</sup>
T <sub>g</sub>	~76°C	~88°C
T <sub>m</sub>	250-270°C	210-230°C
E-modulus	2.1-2.2 GPa	3.1-3.3 GPa
Yield strength	50-60 MPa	90-100 MPa
Quiescent Crystallization time	2-3 min	20-30 min



**Figure 15.** Oriented PEF: Barrier properties [35].

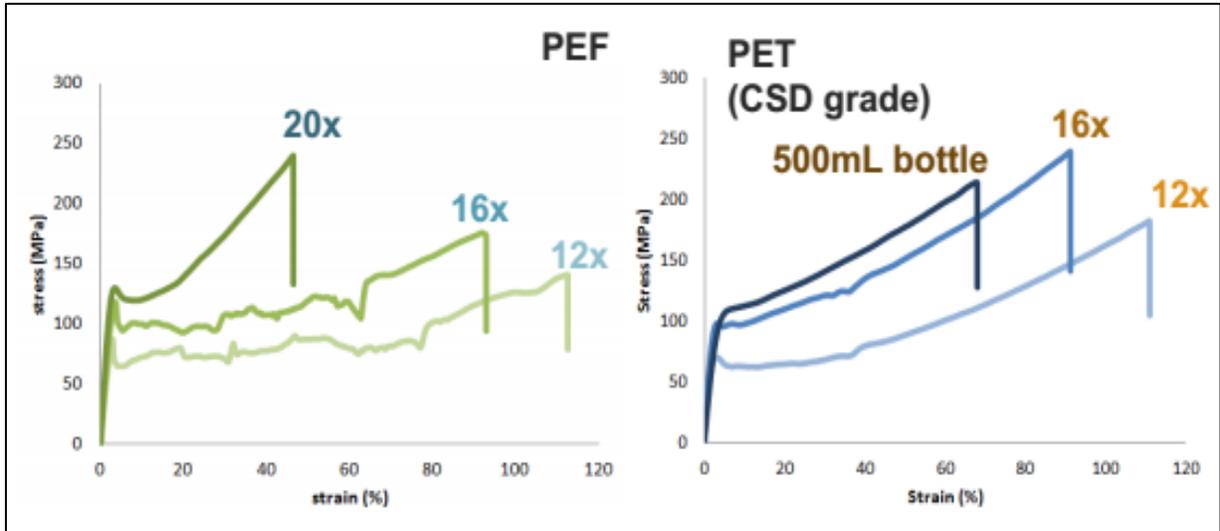


Figure 16. Oriented PEF: Mechanical Properties [35].



Figure 17. Strong shape flexibility for O<sub>2</sub> sensitive products with PEF [35].

Compared to same bottle in PET:

- 6-10x O<sub>2</sub> shelf life
- 4-6x CO<sub>2</sub> shelf life
- Heat resistance

Opportunities [35]:

- Clean labels (preservative free) with a hot fillable O<sub>2</sub> barrier bottle.
- (Bio-based) packaging differentiation
- Event drinks: Switching from glass to plastic e.g. for events or long transport

## **2.4 Polyesters in food and liquid packaging**

Packaging of food and liquid were primarily done for ease of movement and trading of products over long distances. Although packaging of food and liquid has evolved over time and apart from eschewing food contamination, promoting food safety and retaining nutritional qualities of foods, packaging now provides important features which customers find crucial. Some of these features are tamper evidence, resealability, display of product information and reuse or recycling features. Both perishable and non-perishable foods are part of these commodities. Packaging industry especially for perishable food in recent decade has experienced transformation into sophisticated and intelligent service industry [13]. This industry has exploited the advantage of the recent development in material science, manufacturing and process engineering coupled with advancement in food science. Packaging of food and liquid serves many purpose, such purposes include the ability to contain and protect food, keep food safe and secure, retain food quality and freshness, and to extend its shelf life. However, the affordability of packaging to worldwide consumers is highly important and its ability to naturally biodegrade upon disposal. Rapidly growing sectors of the global market such as fast food businesses (ready meal, snacks, on-the-go beverages and manufactured food) are unarguably thriving because of the unending successes happening in the packaging industry [14]. The latter half of the twentieth century has been indeed characterized with incredible growth in the industry owing majorly to the innovations made in the petrochemical industry.

Nevertheless, synthetic plastics suffer a major hitch which is its recalcitrant nature to biodegradation and consequently has ensued into a major setback for companies such as municipal solid-waste (MSW) management. This of course poses environmental threat to landfill issues in Europe and the world at large. Additionally, the uncontrolled disposal means adopted for single-use plastic packaging in some developing countries without the nitty-gritty of vibrant MSW practices really constitutes negative impacts on quality of life on the inhabitants and the

environs. The advent of bio-polyester is birthed as a result of the increasing European's consumer markets tending in the direction of greener packaging, (i.e. packaging from recyclable materials, recycled materials and re-usable packaging, reduced material use (light weighting) and bio-derived polymers). The issue of sustainability takes the lead on EU's agenda and for a couple of years now. This indeed is the motivation behind the development of sustainable alternatives which is aimed at preserving resources for future generations as well as preserving our planet [36].

#### **2.4.1 Current raw materials sources for typical bio-polyesters**

The production of bio-based polyesters can be from several plant-based raw materials. Also, natural polymers such as macromolecules that are available naturally in plants are utilized, and smaller molecules, such as sugar and fatty acids (plant oils), are possible to be used for raw materials during the production of bio-polyesters. Bio-based polymers can be produced using all of these renewable resources by modification and processing [37].

#### **Natural Polymers**

Polymers synthesized by any living organisms are referred to as natural polyesters. Examples of this may be; polysaccharides, protein, or lignin, which acts as energy storage or have a structural functional unit for the cells or the organism as a whole [37].

#### **Polysaccharides (Carbohydrates)**

Polysaccharides are the most important biopolymers, which have more than one sugar unit.  $\alpha$ -polysaccharides for example hold an energy storage unit in starch, while  $\beta$ -polysaccharides serve as the structural substances [38].

### **Succinic acid**

Anerobic fermentation is utilized to produce bio-based succinic acid, making use of various types of microorganisms. e.g, succinic acid is derived from glucose by the rumen organism *Actinobacillus succinogenes*; and as well be produced by *Anarobiospirillum succiniproducens* making use of glucose or lactose, sucrose, maltose or fructose in exchange for carbon sources. Several feedstocks, such as cornstarch, corn steep liquor, whey, cane molasses, glycerol, lignocelluloses, cereals, and straw hydrolases could be used for succinic acid production [39].

### **Adipic acid**

This bio-based adipic acid is yet to attain its full potential since it is still under development and its production is not on a large scale. However, Verdezyne and Rennovia are producing adipic acid by developing a process using bio-based route. The bio-based process employed by verdezyne applies genetically modified enzymes conversion process which enables glucose to be fermented to adipic acid, while Rennovia's method entails converting glucose to glucaric acid by using air oxidation, the glucaric acid is then converted to adipic acid by hydrodeoxygenation [40].

### **Terephthalic acid**

Terephthalic acid is produced from bio-based p-xylene through a process known as depolymerization of lignin [41]. Lately, the production of terephthalic acid derived from limonene is under patent. This process is made possible by the hydrogenation of limonene to p-cymene making use of zeolites and this compound is subsequently oxidized. However, this aforementioned method is still under development and it is not yet produced on an industrial scale, mainly due to the scarcity of limonene [42]

## **Ethylene glycol**

Biofuel is produced using the chemical activity of microbial ethanol from starch and sugar. Bioethanol can be dehydrated to ethylene in the presence of catalysts such as activated clay, phosphoric acid, sulfuric acid, activated alumina, metal oxides and zeolites [43]. Making use bio-based ethylene, one feasible way to obtain bio-based ethylene glycol is through the conventional route process, whereby direct oxidation is applied to produce ethylene oxide and finally by thermal hydrolysis [44].

## **2.5 Biogenic Materials**

### **Plant Oils**

Glycerine and different fatty acids are the typical composition of vegetable oil. Together with their application in human and animal food, as lubricant or source of energy. A number of vegetable oils can be used in the production of bio-based plastics [45].

### **Monomers**

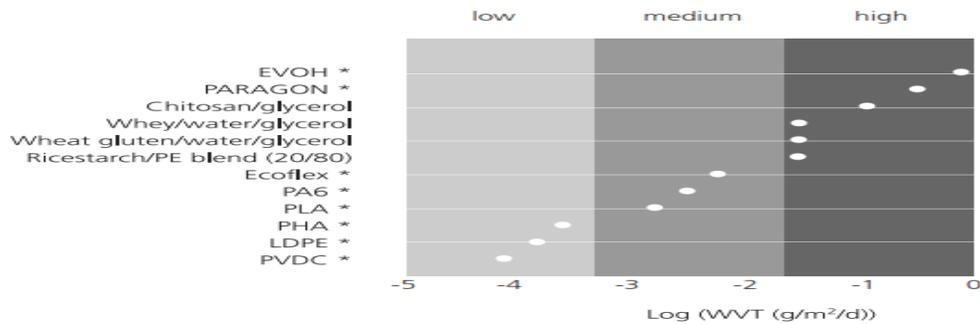
There is a range of monomers and dimers that is utilized to produce bio-based plastics. In the production of bio-based polyesters, some specific bivalent alcohols from renewable resources are partly used, bio-based 1,3-propanediol has been marketed as bio-PDO, and 1,4-butanediol will soon be commercialized as bio-BDO produced from renewable raw materials e.g. maize and starch [30]. In recent times, succinic acid ( $C_4H_6O_4$ ) has been another significant substance of research, which is produced by fermenting starch and oligosaccharides. Lactic acid is an essential type of monomer used for PLA [46].

## **2.6 Typical Material Properties Requirements**

### **2.6.1 Water Vapour Transmittance**

One of the major manufacturer's challenges is the hydrophilic nature of many bio-based polymers and most food applications demand material that have high resistance to moisture.

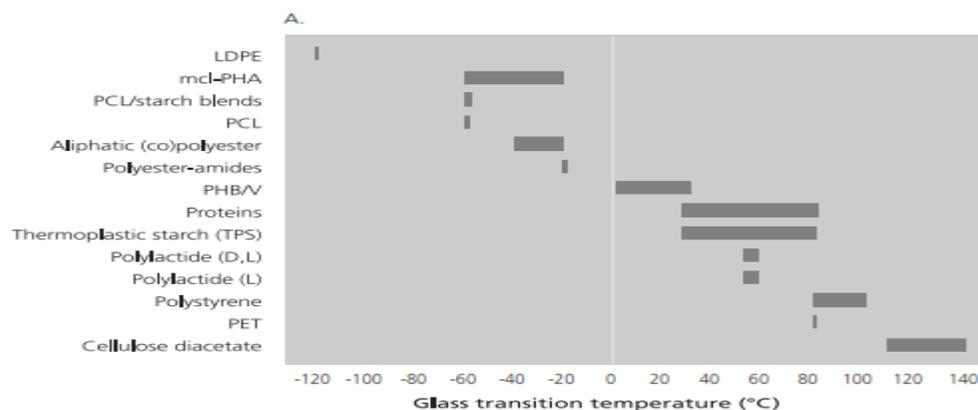
Although, when the water vapour transmission rate of different bio-based material is compared to materials based on mineral oil, then it can be noticed that it is viable to produce bio-based materials with water vapour transmission rates close to the values obtained from some conventional plastics. Moreover, if the package requires a high water vapour barrier property, then only small number of bio-based materials applies [47].



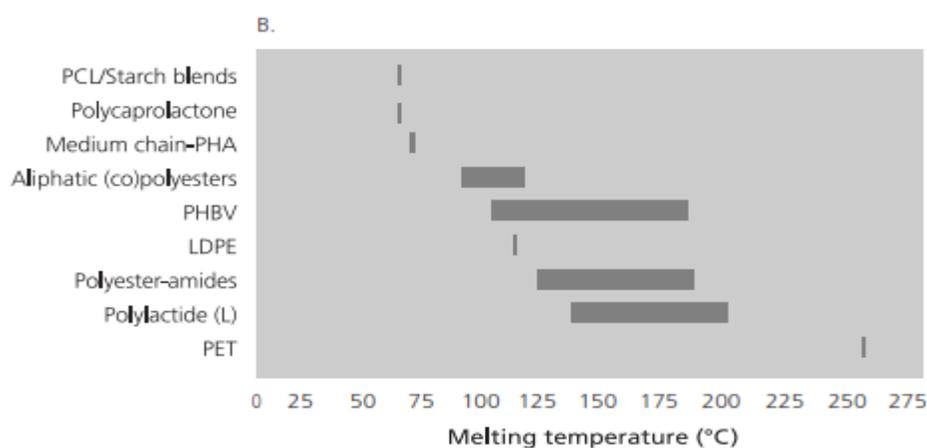
**Figure 18.** Water vapour transmission rate of bio-based materials versus conventional packaging materials based on mineral oil. Water vapour transmission rate of materials indicated with \* was measured by ATO (Wageningen, NL) at 23<sup>0</sup>C, 50% RH. [47,48].

### 2.6.2 Thermal and Mechanical Properties

Thermal and mechanical properties of both bio-based and conventional polymers materials are essential during production and as well during the application of the products derived from these polymer materials. Certain mechanical properties for example, modulus and stiffness show exceptional similarities when compared to conventional polymers [49]. Glass transition temperature is an important factor for packaging selection under a specific temperature application of polymer, *i.e.* it is used to determine the usability and processability of a particular bio-based polymer for a given application. Therefore, it is recommended to use a glass transition temperature lower than the freezing temperature for packaging of frozen products [50].



**Figure 19.** Comparison of the thermal properties of bio-based polymers with conventional polymers against Glass transition temperature [49].



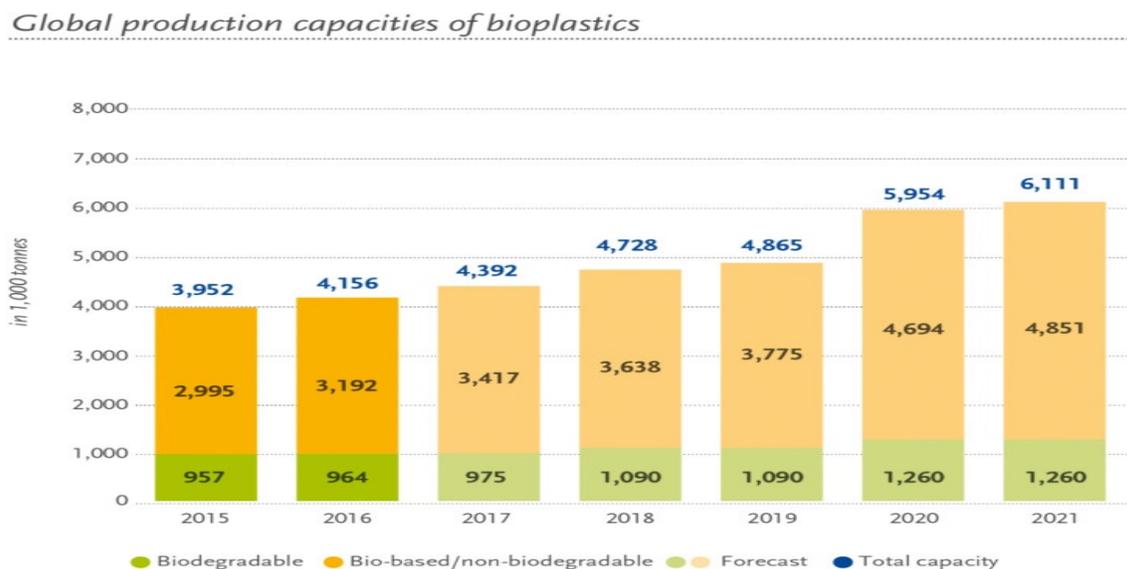
**Figure 20.** Comparison of the thermal properties of bio-based polymers with conventional polymers against melting temperature [49].

In Figures 19 and 20, a comparison of the thermal properties of different bio-based polymers with existing polymers was conducted, and it was seen that the modulus of bio-based materials ranges from 2500 to 3000 MPa and lowers for stiff polymers, such as thermoplastic starches, with a value of 50 MPa and on the same level for rubbery materials like medium chain polyhydroxyalkanoates. In addition, the modulus of most bio-based and petroleum-derived polymers can be adjusted to be in compliance with the required mechanical properties by various process, such as of plasticizing, blending with other polymers or fillers, crosslinking or by the

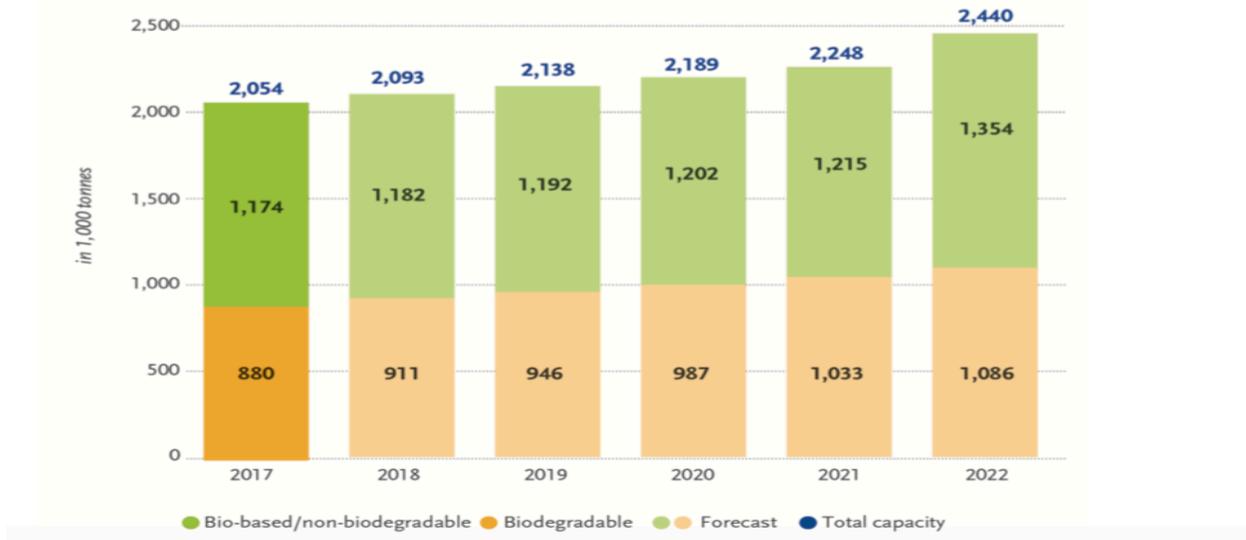
use of fibres. Polymers such as cellulose can be used for materials that require special mechanical properties [49].

## 2.7 Market Volumes, Producers

In 2016, the market size information regarding bio-based packaging was obtained from European bio-plastics (EuBP) using nova-Institute’s market study. The estimated global production capacity of bio-plastic according to European bio-plastics is estimated to grow by 50 percent in the mid term, from around 4.2 million tonnes in 2016 to about 6.1 million tonnes in 2021, while the latest market data illustrates an increase from 2.05 million tonnes to 2.44 million tonnes between 2017 to 2022 as shown in figure 22 [51].

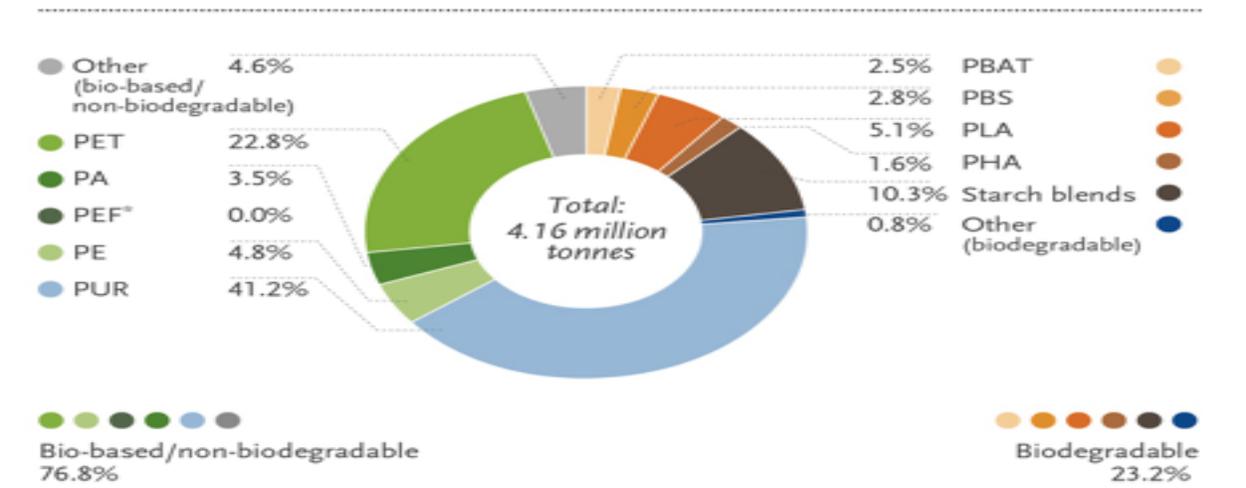


**Figure 21.** Global production capacities of bioplastics (European Bioplastic, nova institute, 2016) [51].



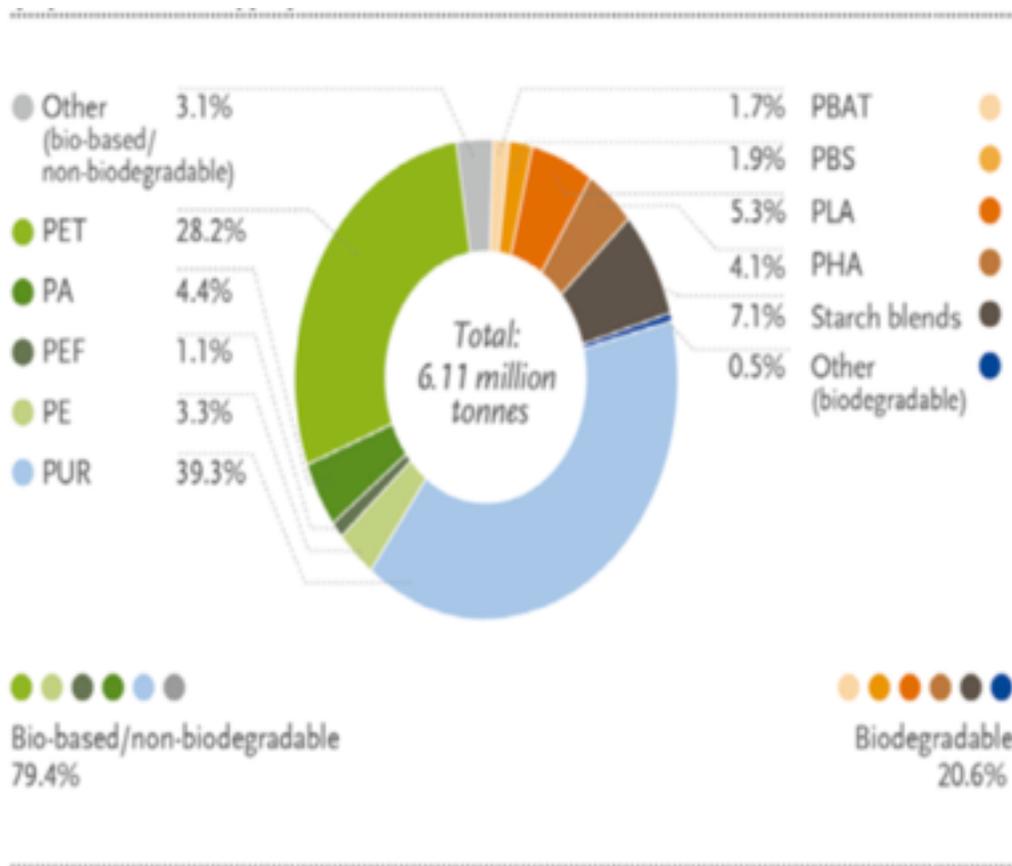
**Figure 22.** Global production capacities of bioplastics 2017-2022 (European Bioplastic, nova institute, 2017) [51].

Figures 21 and 22 represent the production of bio-plastics into different categories. The focus was on the production capacities of bio-plastic on a global scale.



\*PEF is currently under development and predicted to be available in commercial scale in 2020

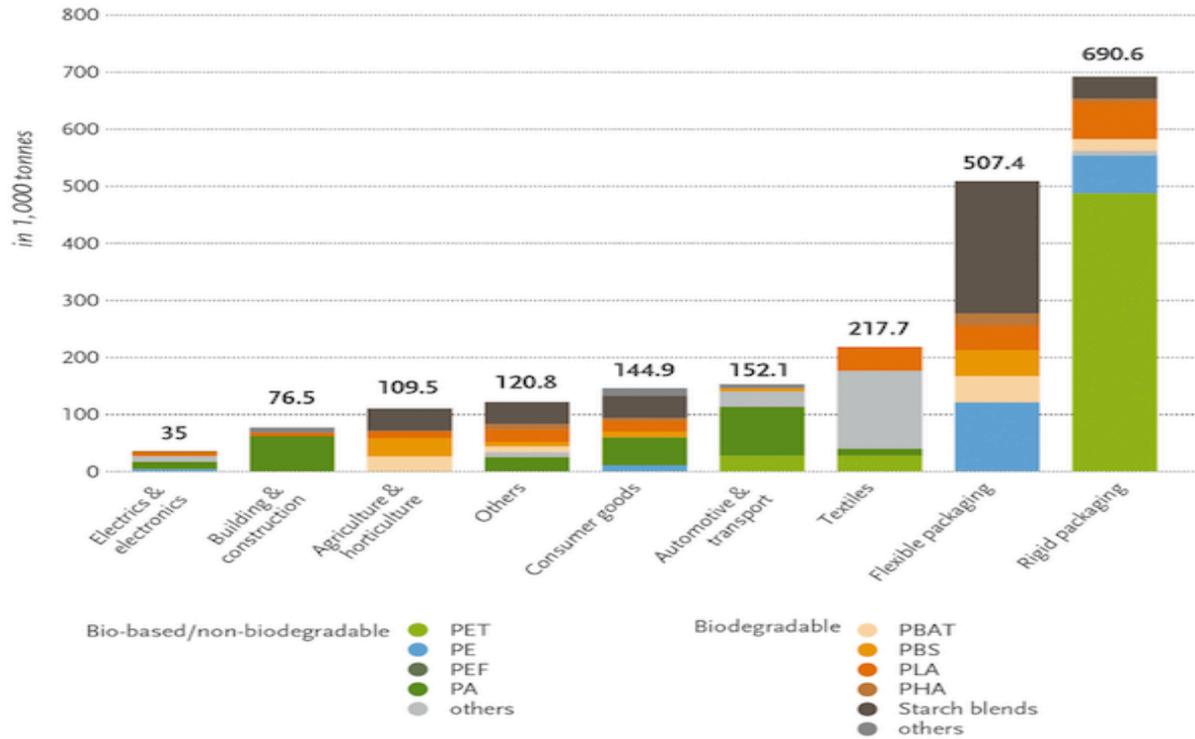
**Figure 23.** Global production capacities of bioplastics 2016 (by material type) [51].



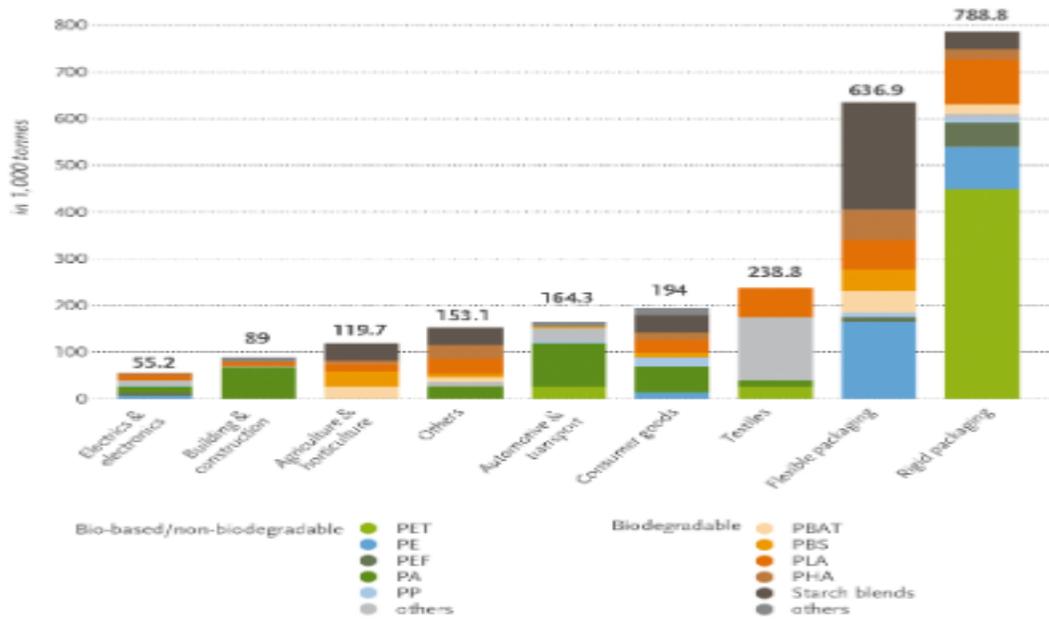
**Figure 24.** Global production capacities of bioplastics 2021 (by material type) [51].

As illustrated in figure 23, the main drivers of this predicted growth are Bio-based, non-biodegradable plastics, such as polyurethanes (PUR) and drop-in solutions, such as bio-based PET, with PUR occupying about 40 percent and PET over 20 percent of the global bioplastics production capacities. Biodegradable plastics (PLA, PHA, and starch blends) are expected to increase from 0.9 million tons as recorded in 2016 to almost 1.3 million tons in 2021[51].

Figure 24 further shows the global production capacities of bioplastics by material type as forecasted by 2021, with bio-based PUR and PET dominating the market. PUR share is predicted to remain constant, while PET share is expected to experience an increase in value from 22.8 % to 28.2 % by 2021.



**Figure 25.** Global production capacities of bioplastics in 2017 (by market segment) (51)



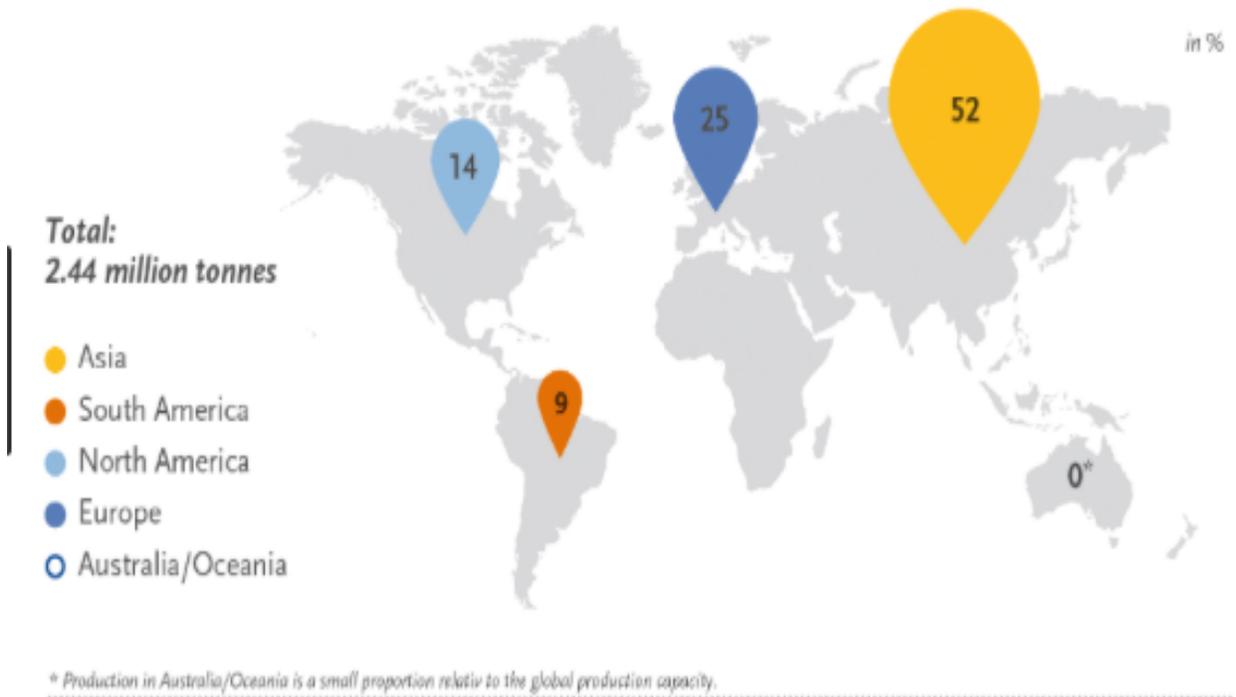
**Figure 26.** Global production capacities of bioplastics in 2022 (by market segment) (51)

Figure 25 illustrates a bar chart providing information on different market segments where bioplastics are utilized and topping the chart are flexible and rigid packaging. The growth in the use of bioplastics for packaging could be attributed to the increasing demand for sustainable products by stakeholders.

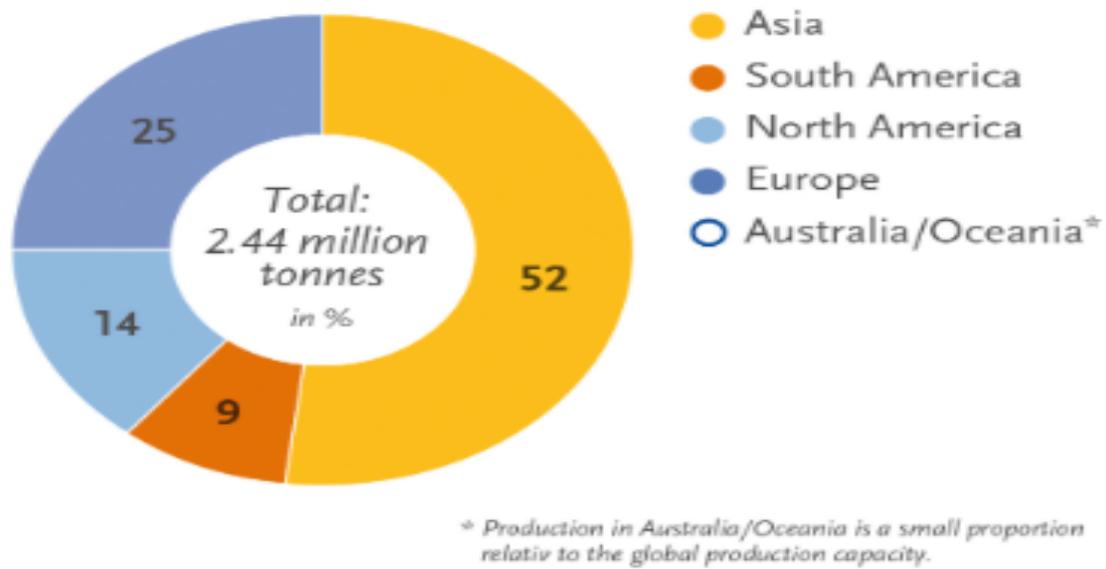
Furthermore, the future looks promising for bioplastics as represented in the chart, with rigid packaging leading with an increase in 14.2% between 2017 and the predicted year 2022 (51)



**Figure 26.** Global production capacities of bioplastics in 2017 (by region) (51)



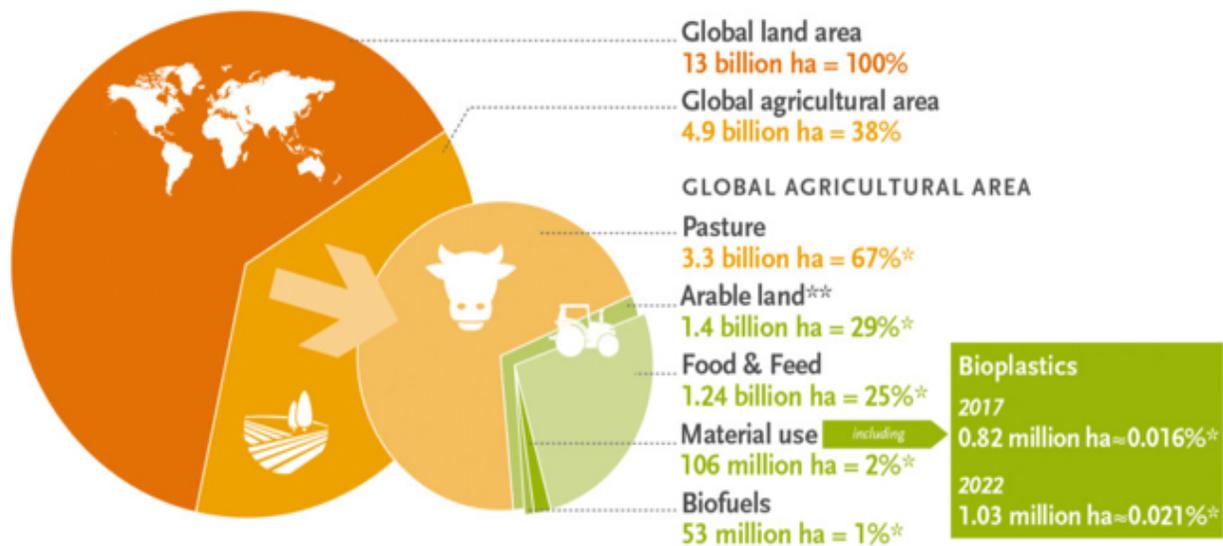
**Figure 27.** Global production capacities of bioplastics in 2022 (by region) (51)



**Figure 28.** Global production capacities of bioplastics in 2022 (by region) (51)

The global production of bioplastics varies in different continents and it can be seen from figure 26, Asia has the largest production capacity with over 50 % production of bioplastics in 2017. Europe is ranked highest in research and development sectors and is known to have the largest market globally.

The projected production capacities for bioplastics in 2022 by region is expected to rise in Europe from 18 to 25 %, such development is as a result of Europe being the central part for the entire bioplastics industry. On the other side, there happens to be a drop from 56 to 52 % in the Asian market (51).



**Figure 29.** Land use for bioplasites 2017 and 2022 (51)

The production of bioplastics requires the use of land for the grow of renewable feedstock and its land area amounts to 0.82 million hectares in 2017, while the same factor of production is expected to increase to 1.03 million hectares by 2022, which is based on market growth prediction for the next five years.

**Table 2.** Bio-based packaging and biodegradable materials currently available in the market [51].

MATERIAL	SUPPLIER	TRADE NAME (IF KNOWN)	POLYMER LINKAGE
<b>Biodegradable materials based on natural renewable sources-Bio-polymer</b>			
PHB/PHV (Polyhydro-xyalkanoate)	Was Monsanto Biomer	Biopol Biomer	Ester Ester
Cellulose acetate	Courtaulds Mazzucchelli		Acetal Acetal/Ester
Poly lactide/PLA	Cargil Dow Polymer Mitsui Hycail Galactic	NatureWorks PLA LACEA Galactic	Ester Ester Ester Ester
Starch	National starch Avebe	Eco-FOAM Paragon	Ester Ester
PEF (PolyEthyleneFuranote)	Alpha Avantium	PlantBottle™	Ester
Bio-PET (PolyEthyleneTerephthalate)	Alpla	PlantBottle™	Ester
<b>Biodegradable Materials Based on Blends of Biopolymer and Synthesis</b>			
Starch-based	Novamont Biotec Earth Shell Biop	Master Bi Bioplast Earth shell Biopar	Acetal/Ester Acetal/Ester Acetal/Ester Acetal/Ester
<b>Biodegradable Materials Based Wholly on Synthetics</b>			
Copolyester	BASF Eastman Chemicals	Ecoflex Estar Bio	Ester Ester
Polycaprolactone	Union Carbide Solvay	Tone polymer CAPA	Ester Ester
Polybutylene Succinate	Showa Highpolymer	Bionolle	Ester
Polyesteramide	Bayer	BAK	Ester
Polyesterurethane	Bayer	MHP 9029	Ester
Polyester Co-polymer	Bayer	Degranyl VSP42002	Ester
Polyactic acid	Fortum		Ester
Polyester	Dupont	Biomax	Ester

Ongoing advancements in white biotechnology, which is a process that uses living cells derived from yeast, moulds, bacteria and plant to synthesize products that are vulnerable to degradation. Furthermore, this energy efficient and minimal waste technological initiative has also contributed to the production of bio-based polymers and other chemicals from renewable resources [52]. The first set of bio-based polymers producers used food resources such as corn, starch, rice, etc. as their main resources for biopolymers production. As the rise in debate on food-versus-fuel emerged the focus of technologist and technology used diverted to cellulose-based feedstock with more emphasis on waste from wood and paper, food industries, and even stems, leaves and solid municipal waste streams. Interestingly, the abovementioned waste management technology is already in the agenda, but the development of a full spectrum of chemicals based to enhance these technologies may possibly take another 20 years [53].

Urgent attention is required in years to come in management of raw materials, cost of production and performance of bio-based materials.. Lack of experience in operation and management of modern technologies and estimation of supply/demand balance are some of the reason why building large-scale plants might likely be unachievable. For the economic viability of these new technologies, the development of the following sectors is important;

1. Logistics for biomass feedstock's
2. New manufacturing routes by replacing existing methods with high yields
3. New microbial strains/enzymes
4. Efficient downstream processing methods for recovery of bio-based products.

Most bio-based industries are focused primarily on making bio-versions of existing monomer and polymers. Since this existing monomers and polymers are well known, its' no doubt easier to replace such existing product with a bio-version which will have similar performance and good enough all polymers mentioned above frequently display similar properties of current fossil based polymers. In recent times, enormous amount energy have been channelled into invention of new bio-based polymers with higher performances and value, a good example is the introduction of new grades of PLA by Nature works LLC, with higher thermal and mechanical properties similar to thermoplastic elastomer. Also, a lot of improvements are currently ongoing to develop various polyesters, polyamides, polyhydroxyaloknates, etc. which is expected to have

a high diversity in their concluding attributes and will be used in applications such as automotive, electronics and biomedical [54].

A major disadvantage of bio-based polymers is its inability to blend in current processing equipment. In accordance with comprehensive knowledge in additive-based chemistry, aimed at enhancing the performance and processability of conventional petroleum-based polymers, likewise such perception can be applied to further develop the performance of bio-based polymers [55]. PLA and PHA are some of the additives being developed for the enhancement bio-based polymers. But apparently, the commercialization of the additive for bio-based polymers is still in its infancy, which obstructs major development efforts to emanate, according to some key additive supplier companies. Petroleum-based polymer performance has long been enhanced with the use of nanoparticles as additives [56].

Global demand for food and energy is anticipated to increase over time since there is competition for feedstock, in present times, the use of renewable feedstock in manufacturing bio-based monomers and polymers is not sustainable since it compete with requirement for food-based products. In terms of market demand, an expansion of the first generation method of producing bio-based monomers and polymers will have an adverse effect on biomass resources and thereby causing some level of threats to food production as well as sustainability of biochemical and biopolymer production [53]. Consequently, the European commission has indicated interest in sustainability by placing preferential consideration to non-food sources of sugar for biofuel production [57]. However, several initiatives are still in progress to utilize cellulose-based feedstocks for the production of usable sugars for biofuels, bio-chemicals, and biopolymers [58].

## **2.8 Safety and Health Issues**

Packaging acts as a barrier and normally renders a high level of protection against external hazards. However, potential problems might arise when undesirable interactions between food and packaging materials occur and this can be effectively overcome with adequate packaging. The European Food Safety Authority (EFSA) holds the main responsibility to make sure that packaging material in contact with food is not harmful. Undesirable interaction between food and packaging is migration and it is actually often times caused by materials and articles coming in

contact with food [59]. Industrialized countries have been forced to legislate food preparation and packaging as a result of chemical contamination of food. Though, some bio-based materials, like paper and regenerated cellulose are well defined under a harmonized EU food regulation safety. Also, development of new materials has been in progress and the producers are responsible as to ensuring the safety and suitability for food contact. The safety of food contact materials is assessed based on certain factors, like identity, toxicological risk and migration limits [59].

### **2.8.1 Legislation and Regulation Aspect**

The European Union (EU) Framework Regulation (EC) No. 1935/2004 controls all safety of food contacts materials and articles regardless of their source. The Frameworks clearly states the basic requirement for food contact materials and articles, its main aim is to ensure food safety, consumer protection and for proper standards in trading within the EU. Article 3 of the regulation, which specifies general requirements states:

“1. Materials and articles, including active and intelligent materials and articles shall be manufactured in compliance with good manufacturing practice so that, under normal or foreseeable conditions of use, they do not transfer their constituents to food in quantities which could:

(a). Endanger human health;

Or

(b). Bring about an unacceptable change in the composition of the food;

Or

(c). Bring about deterioration in the organoleptic characteristics thereof.

2. The labelling, advertising and presentation of a material or article shall not mislead the consumer.” [60].

The “Practical Guide”, a European Commission document gives unequivocal information and guidelines as regards the necessary directives required for materials and articles intended to come in contact with foodstuff. The list established for plastics is restricted to monomers and starting substances for plastics. Any substance used in manufacturing macromolecule, and which constitute the repeating units of a polymer chain or polymer network of any substance used in the manufacture of a plastic for food contact application can be clarified as monomer and starting substance. In accordance to Directive 90/128/EEC the following substances are included in the definition:

- Substance undergoing polymerization which include polycondensation, polyaddition or any other similar process, to manufacture macromolecules.
- Natural or synthetic macromolecules substances used in the manufacture of modified macromolecules if the monomers, or the other starting substance required to synthesize the monomer are not included in the list.
- Substances used to modify existing natural or synthetic macromolecular substances.

Information for the applicant on mixture, synthetic mixtures, mixtures from natural sources and process mixture can be found Practical Guide [59].

## **2.9 Recycling and Reuse**

Material recycling is defined in accordance with European standard EN 13430 and EN 16848 (adapted from ISO 18604) as the reprocessing of a used product material into a new product. Recycling of packaging materials has been a subject of interest in the production and packaging industries. Consequently, with the rising need to produce fewer greenhouse gases, avoid incineration, and produce fewer toxic pollutants, recycling of packaging is obviously a better alternative to successfully eschew all problems faced with in this sector. Coca-Cola demonstrate their adherence to this course with the introduction of PlantBottle™ which is fully based on Bio-PET with a combination of PET recyclates. Also, PLA is already being industrially recycled and notable industries are Huhtamaki and Desch, likewise PLA recyclate is now marketed to a limited extent for the production of PLA flower pots [63].

### 2.9.1 Reusable packaging

One other end used phase attracting a great deal of attention is “reusable packaging”, which is designed for reuse without impairment of its protective function, such as the revolutionized concept termed “Eco Connect Bottle System” whereby PET bottle, primarily designed as a single used package is repurposed for construction of different household items like desk, table and toys as depicted in figure 30. This concept is however aimed to reducing plastic waste bottle from landfill, which is a move towards sustainability since PET bottle is non-biodegradable in nature [61].



**Figure 30.** Eco connect bottle system [61].

### 2.9.2 Recycled polyethylene terephthalate (R-PET)

Recycled polyethylene terephthalate (R-PET) is a form of plastics that has been formerly used for packaging, e.g beverage bottles. A process known as recycling, such as collecting, sorting, cleaning, and transformation has been applied so as to make it reusable for food packaging. It is economically viable based on the fact that R-PET can be used multiple times to produce bottles, since it is obtained from collected used PET bottles.

The benefits offer by R-PET include:

1. Reduction of carbon footprint
2. Reduction of emission pollution
3. Reduction of environmental waste

Furthermore, the application of R-PET gives the possibilities of avoiding several energy intensive steps during manufacturing process, thereby leading to reasonable reduction in CO<sub>2</sub>. In addition, in terms of food contact in the plastic package, R-PET is mainly used as an intermediate layer during food packaging, so there is no direct contact between R-PET and the content in the package. The required barrier is obtained from the top and outer layers which are in contact with the food [62].

### **2.9.3 Composting**

Compostability is the ability of an organic material to be transformed into compost through a process known as composting. Composting is therefore the disintegration of organic matter by a mixed microbial population in a moist, warm, aerobic (in the presence of oxygen) environment under controlled conditions. According to the European Directive 96/62/EC, it specified that composting of packaging waste is a fraction or element of recycling, since it's the transformation of the original product into a new product whereby it's regarded as the compost [63]. In tandem with the standard, a compostable material for packaging is such that conforms with EN13432 framework. A plastic packaging can only be called compostable if it demonstrated that [59]:

- The packaging material and its relevant organic component are naturally biodegradable;
- Disintegration of the packaging material takes place in a composting process for the organic waste;
- The packaging material has no adverse effect on the composting process;
- The packaging material does not negatively influence the quality of the compost.

Any certified packaging with EN13432 is allowed to carry the seeding label and will have its own P number. Also there are other certification programmes, such as the Vincotte “Ok Compost” programme.



**Figure 31.** Label showing the products are compostable according to EN13432: Vincotte, Seeding label [63].

When there is reintegration of the recycled material back into the market then it can fully be accepted that composting is a recycling process. Although, an environmentalist perspective means the integration of the compost in the bio-geo-chemical cycles of the carbon with the restoration of the natural ecological cycles.

Although, compostable bio-plastics require specific composting facilities for degradation, they may be recycled with normal plastics but they may degrade during the recycling and thus resulting in contamination of other plastics as well. European bio-plastics recommend that compostable need an environment with specific ratio of CO<sub>2</sub>, oxygen and nitrogen [63]. Among the few most critical factors for bio-plastics, recycling has emerged one of them. However, one approach to overcoming this challenge is by labeling bio packaging and adopting special sorting techniques during recycling which may lead to an additional investment as shown in figure 31.

### **3 EVALUATIONS AND ANALYSIS**

This chapter entails the evaluation and analysis based on the market situation, which is centered on the role of bio-based polyester in food and liquid. In time past, synthetic polymers are the majorly used packaging material due to their indispensability to modern sciences and technology.

#### **3.1 Market Feasibility Analysis**

Researchers over the few years have differing claims based on their findings about the market feasibility analysis of the Bio-Plastic industry. A summarized version of their projected outcomes with wider time coverage up to 2020 is presented in table 3 below, which is accompanied with a review of their diverse market studies. Although, there are no consistent claims by most researchers on the industry but most maintained the same opinions about bioplastic growth, expected to range between 16-29% CAGR. Non-degradable plastics such as PE, Bio-PP and Bio-PET are projected will be the highest growth.

In additional, biodegradable plastics such as PHA and PLA are estimated to show positive growth but on the contrary, are most likely to suffer market loss in terms of values to the non compostable bioplastics. However, one other challenge obstructing the actual growth of bio-based polyester is the inability to develop a cost effective technology that supports production on a commercial scale from non-edible feedstocks for example wood pulp, waste fibers and other materials [64]

**Table 3.** Projected Supply and Demand of Bioplastic from Various Studies

<b>STUDY</b>	<b>REPORT DATE</b>	<b>PROJECTED GLOBAL CAPACITY END OF PERIOD (MILLION TONS)</b>	<b>PROJECTED GLOBAL CAPACITY END OF PERIOD (MILLION TONS)</b>	<b>TIME PERIOD COVERED</b>
Nova Institute	2013	12	12	2020
EU. Bioplastic	2013	6.2	Not given	2017
Freedonia	2011		1.0	2015
World Bioplastic	2009		0.9	2013
Freedonia	2008		0.816	2013
PR Newswire	2010		0.138*	2014
EU Bioplastic	2007	1.36		2011
PROBIP	2009	2.94		2020
SRI	2010		0.281*	2014
SPE	2010		0.75	2014
BCC Research	2010		3.231	2015
PIRA			0.884**	2015-2020

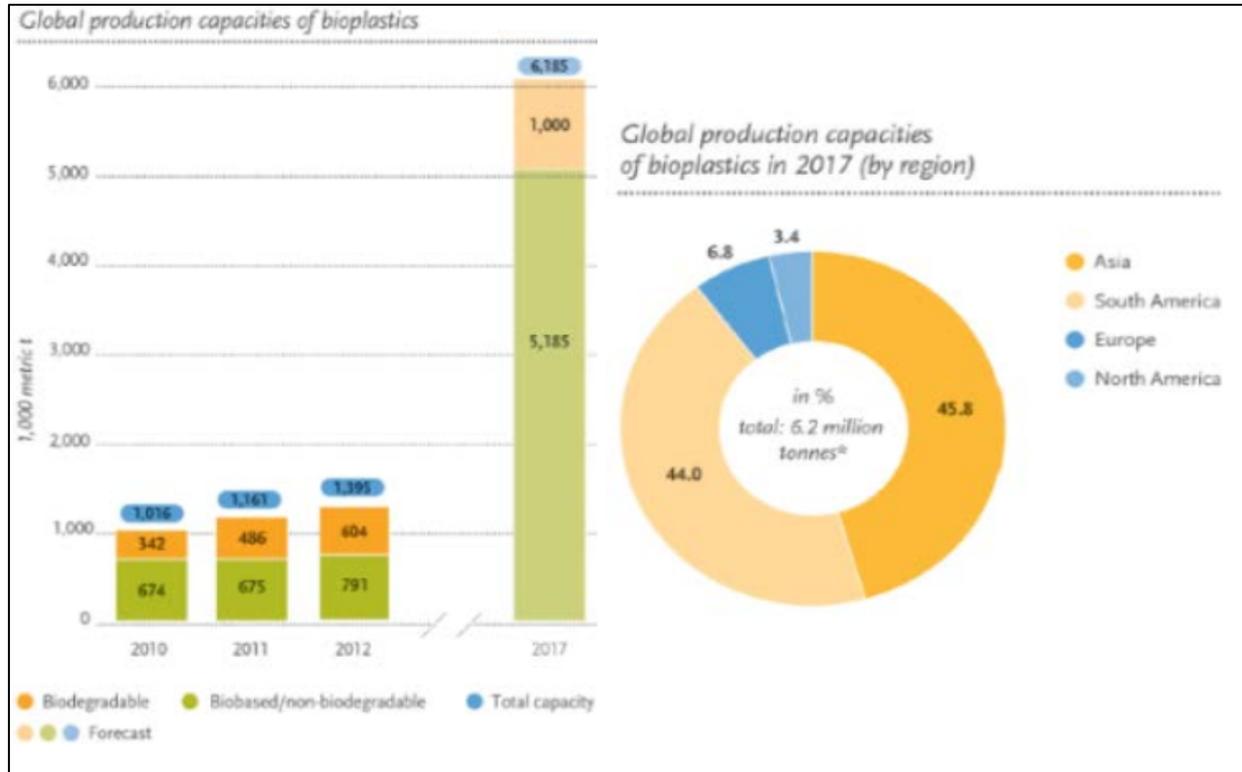
**N.B:** \*Biodegradable plastic only

\*\*Biodegradable packaging only

### 3.1.1 Review of Bio-Plastic Industry by Major Market Studies (European Bioplastic Study)

Bio-based (non-biodegradable) under the bio-plastic group is anticipated to have the biggest boost with the bio-plastic market forecasted to appreciate from about 1.4 million tons which is the annual production capacity to an approximated value of 6.2 million tons by 2017. Their production capacity is projected around 60% by 2017. The leading segment in the bio-plastic application is the packaging market and as a result new solutions are much needed to contribute to reducing the fossil feedstock dependency, to offer more recycling and recovery options, and to minimize the carbon footprint of packaging. [64].

Figure 32 shows the projection of Global Bio-plastic production capacities and a global production of bio-plastic in 2017 by region in the study.



**Figure 32.** Global Bio-plastic Production Capacities in Projection [64]

### US Degradable Plastic Market – August 2010

Projected rise in US demand for degradable plastic is nearly hitting 11% annually i.e. 0.138 million tons in 2014, and the value is \$390 million. The growth of degradable plastic will be promoted by sustainability, pleasant environmental profile, and favourable cost against petroleum-based material and also with the ever increasing demands to reduce packaging waste. Availability in greater amount and a more competitive price structure will make polyactic acid (PLA) grow at a fast pace through 2014. Polyhydroxylkanoaes (PHAs) is projected to more than double reason is as a result of increased availability of PHA plastics and products. Films, molded containers, fiber and starch based plastics are predicted to experience good opportunities in the industry. Good growth is predicted for packaging facilitated with degradable plastics through 2014 [65].

## FREEDONIA GROUP

Sustainable materials, price equality with petroleum-based plastics and improved product performance are consumer penchant that will be stimulant in driving bio-plastic growth. Biodegradable and bio-plastic projected global demand will exceed 1 million tons in 2015 with an estimation of \$2.9 billion [66].

**Table 4.** Projected global demand for bio-based and biodegradable bioplastics (1,000 metric ton) [66].

Year				%Annual Growth	
Region	2005	2010	2015	2005-2010	2010-2015
North America	34	80	242	18.7	27.9
Western Europe	60	125	347	18.8	22.7
Asia/Pacific	33	83	320	20.3	31
Other Regions	3	12	116	32	57.4
<b>Total</b>	130	300	1025	18.2	27.9

In accordance to the study, table 4 gives an insight that shows that bio-plastic have gone past the stage of introduction and it is now experiencing a massive increase in demand in all part of the globe. The increase can be traced to a number of factors including the consumer preference. However, Freedonia expresses concern about the price as that will be the major drive of bio-plastic market breakthrough in this era of rising petroleum cost.

It was seen that 90% of the world plastic market in 2010 accounted for biodegradable plastics, the two dominant biodegradable plastics (starch based resins and polyactic acid PLA) that are both expected to exceed in demand by double through 2015. The fastest gains for biodegradable plastics are polyhydroxyalkanoate (PHA) resins, which are new arrival to commercial market. Non-biodegradable bio-based resins will be the major driving force for bio-plastic demand from 2015 despite the strong advances for biodegradables. Apparently, the production of bio-based PET in industrial scale is predicted to be successful in 10 years to come and non-biodegradable bio-plastics demand will grow from 30,000 tons in 2010 to 1.3 million tons in 2020.

### **Nova Institute Gmbh Study**

Nova Institute conducted a study in the year 2013, and it projected that bio-based polymers production capacity will be tripled from 3.5 million tons to 12 million tons by 2020.

The capital's investment largest share is expected to happen in both Asia and South America and also bio-based drop-in PET and PP and PE/PP polymers and polymer PLA and PHA, which are relatively new shows, having the fastest rates of the market growth. According to their claims from the study, they asserted that this unprecedented study covers all kind of bio-based polymer being produced by 247 companies at 363 locations around the globe. The overall polymer production represents 235 million tons in 2011 while the bio-based polymer production is 3.5 million tons and represented 1.5% of the overall polymer production. Expectations of polymers production is estimated to attain 400 million tons in 2020, the bio-based share is also expected to grow from 1.5% to 3% between 2011 and 2020, indicating an optimistic growth for bio-based production capacity.

Drop-in biopolymers are foreseen to experience the most dynamic development, which are chemically identical to their petrochemical counterparts though are partially derived from biomass. Bio-based PET leads this group and its production capacity is expected to reach 5million tons by the year 2020, using bioethanol from sugar cane. Bio-based polyolefins like PP and PP are the second group and are also based on bioethanol. Compostable bio-based polymers such as PLA and PHA, which are relatively new, are also envisaged at its minimum to increase four times their capacity between 2011 and 2020.

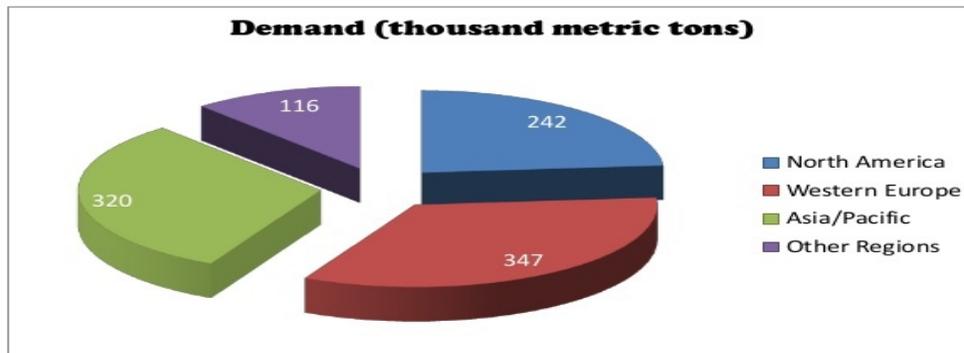
South America and Asia is expected to experience the biggest investment in latest bio-based polymer capacities reasons not farfetched from their easy access to feedstock and favourable political structure. North America's share will decrease from 15% to 13%, Europe's from 20% to 14%, whereas South America's will increase from 13% to 18% and Asia's from 52% to 55%. Dramatic shift are not expected in world market share but every region will witness progress in bio-based polymer production [67].

## World Bio-Plastic, November 2009

In accordance to the result of this study, figure 33 gives a pictorial analysis of the demand of global bio-plastics around the globe in the year 2008. Global demand to grow more than four times by 2013.

### **Bioplastic Industry value: ~ 3 \$ billion**

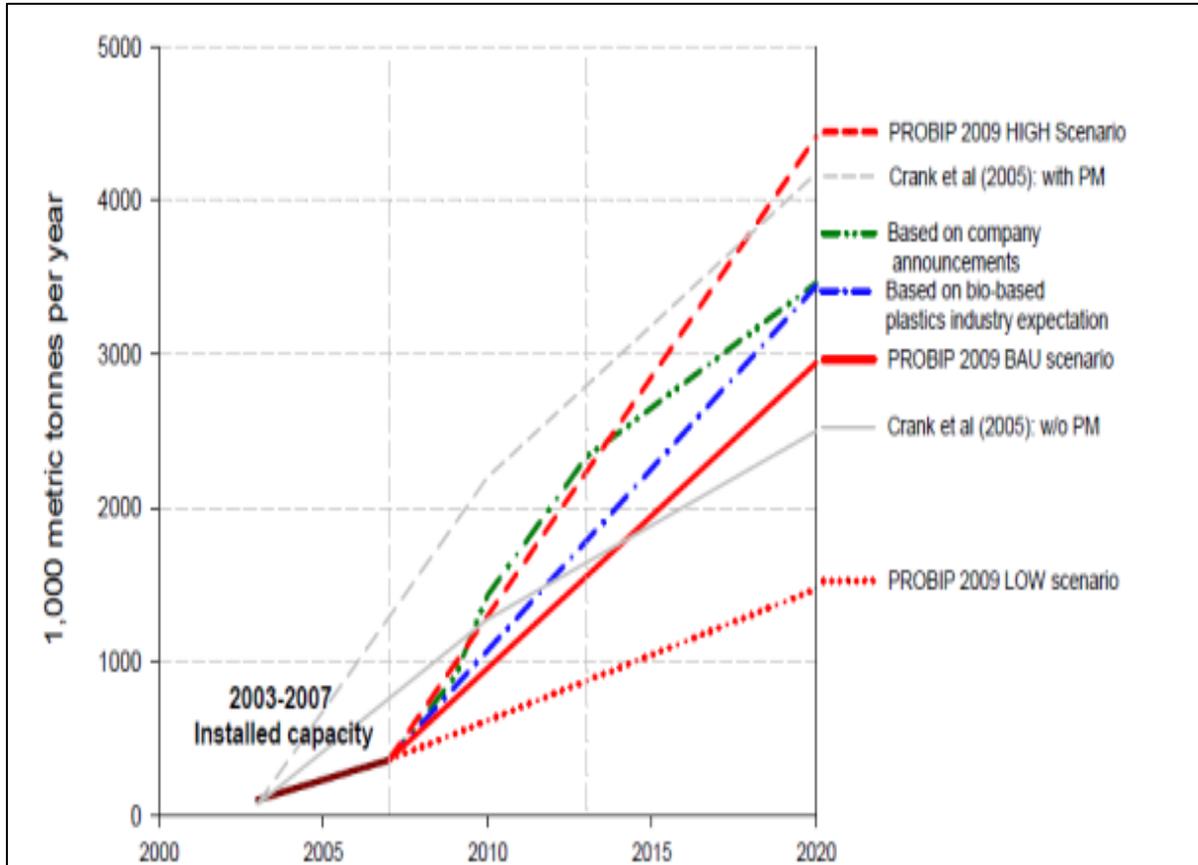
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**Figure 33.** Global Bio-plastics Demand [68].

This study ascertained that demand for bio-plastic that are plant based or biodegradable will be slightly be more than quadruple of 0.9 million tons in 2013 and will be valued at \$2.6 billion. Consumer demand for environmentally sustainable product, increasing restriction on the use of non-degradable plastic product and the development of bio-based feedstock's for commodity plastic resins are the reasons for this experienced growth. Bio-plastic will become more cost-competitive since there is an expected continuation of high natural gas and crude oil prices.

Bio-plastic demand will be principally driven by non-biodegradable, plant based plastic which will rise from 23,000 tons in 2008 to nearly 600,000 tons in 2013. From the statistics gathered Western Europe dominated the local market in 2008. Nevertheless, Asia continent is expected to overtake West European market by 2013. Reasons alluded to high demand of sustainability in Japan, which has encouraged the use of bio-based plastics. Brazil is expected to become the leading producer of bio-plastic [68].



**Figure 34.** Bio-plastics Growth Projection from PRO-BIP (2009) Study [69].

Figure 34 shows the pictorial projection been predicted by the study. This study asserted that bio-polymer has the potential to oust 90% of all conventional polymers if technical challenges are not experienced in commercial scale and feedstock availability, economical hindrances and the smooth transition to green plastics can soon be scale through. This study is the most optimistic study published on bio-plastic capacity projection. It further stated that based on industry expectations the production capacity in 2013 is anticipated to be 2.3 million tons elevating to 2.94 million tons by 2020 under the auspices of business as usual scenario (BAU) [68].

## Assessment Carried out by Jim Lunt and Associates

The table 5 shows the estimated capacities and sales in 2013 for major bio-plastics. This information was gathered based on discussion with key players and mastery of the marketplace.

**Table 5.** Estimated sales and manufacturing capacities for 2013 [70].

<b>PRODUCT</b>	<b>2013 BIO-PLASTICS MANUFACTURING CAPACITY (MILLION TONNES)</b>	<b>2013 SALES ESTIMATES (MILLION TONNES)</b>
Bio-based Polyethylene	0.12	0.06
PLA	0.26	0.2
PHA's	0.02	0.005
Bio-PET	0.66*	0.66*
Others	0.05	0.02
Totals	1.31	1.095

\*Contains only 30% renewable resource based on bio-ethylene glycol

According to this assessment, projected capacity estimated and sales are both lower when compared to those found in EU market but correlates with Freedonia and World Bio-plastic studies. The European Bio-plastic projected capacity in 2011 is close to the actual sales in 2013 before the inclusion of the developing non-biodegradable plastics. Metabolix, the present domestic supplier of PHA does not have any dedicated production plant, and PHA suppliers are still battling with high price barrier.

Cereplast declared bankruptcy, though Meredian plans to produce PHA at around \$2.20/kg but is still not in the market place. Bio-PET, PLA and starch product sales are approaching plant capacities. Projected capacity for bio-plastics in totality is over stated due to high expected growth and announced capacities. Recent oil prices as at when this study was carried out remain at level  $\geq$ \$90/barrel, and such increases will deter rapid entrance of today's major products without improved performance [70].

### **3.1.2 General Overview of the Market study**

Perceived growth based on projected plant capacity and company capacity plans are the two factors established by four of the published studies. Nova Institute study asserted that the overall technical substitution performance for petro-based plastics is demonstrated in the figures. Although, it was believed that it would not happen within a short time due to technical issues in scale up, economic barrier and inadequate availability in feed stocks. The discrepancy among the projections of Freedonia, SPE and BCC for bioplastic demand is wide, but BCC figures seems to be in tandem with Jim Lunt & Associates LLC, which is extremely demanding to align with reality. PRO-BIB projected capacity in the study for 2015 is below the 2015 projections for demand by BCC. 3.21 million tons was the projected global demand for bioplastic by BCC in 2015, which is obvious that it is grossly inflated.

### **3.2 Activities Impacting the Adoption of Bio-Based Polymers**

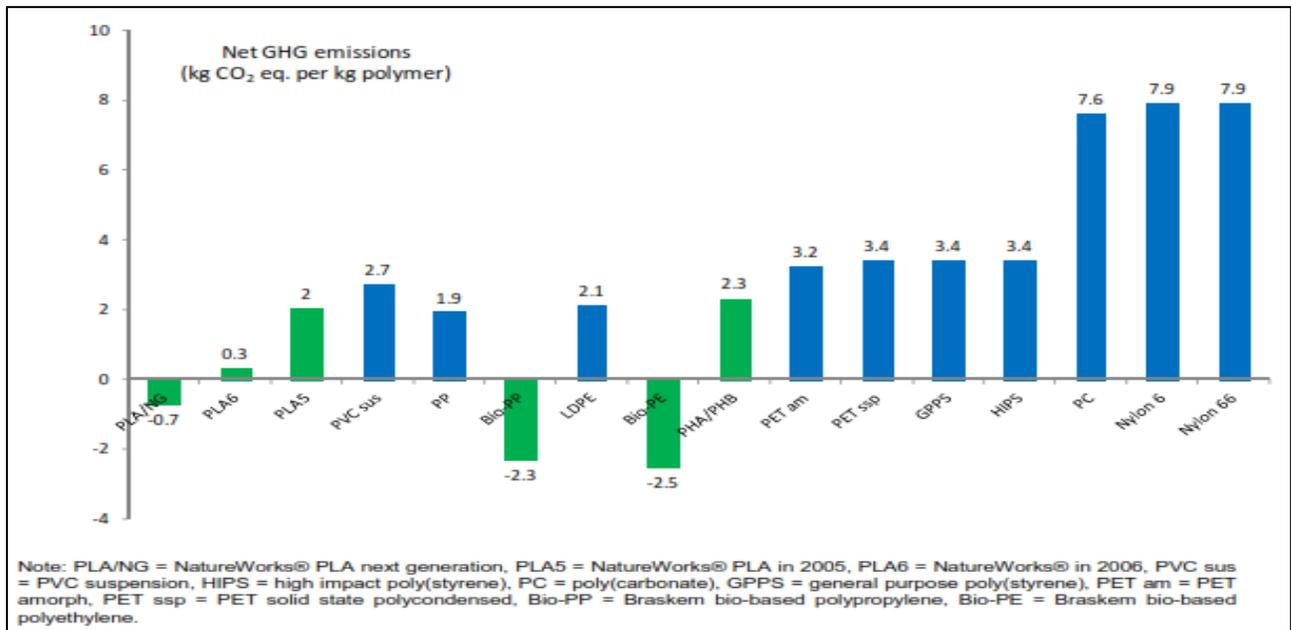
Bio-based polymer increase in usage is driven by the growing consciousness of the impact of conventional packaging means on the environment and as a result demand for sustainable packaging by consumers as increased. Also the need to reduce the dependency on fossil resources and the uninterrupted progression of innovation been experienced in the bio-based polymer industry in materials with better and improved attributes and new functionalities. In line with this, bio-plastic alternatives exist for almost every conventional plastic material and corresponding application. Some factors impacting the adoption of bio-based polymers are listed below.

### 3.2.1 Environmental Issues

#### Climate Change and GHG Emissions

The necessity to cut down GHG emissions throughout their lifecycle is also a crucial driver to the adoption of bio-based polymer over petro-plastics. GHG generation is an important aspect of plastic creation and its impact on climate change is quite enormous. Intergovernmental Panel on Climate Change (IPCC) projections for the stabilization of atmospheric GHG concentration at 450 ppm CO<sub>2</sub> by 2050 require reduction in emissions of 80% compared to the 1990 level, which poses a greater challenge for all sectors of the economy [71].

As illustrated in figure 35, the green bars represent biopolymers while the blue bars represent petro-based polymers. The emissions are on the higher side for the fossil-based polymers, while bio-based polymers show negative and less positive values. However, these are product life cycle evaluations and as such, the impacts associated with recycle, disposal and use are excluded.



**Figure 35.** Greenhouse gas emissions (as CO<sub>2</sub>) for various Petro and Biopolymers.

Source: OECD based on various: [72,73,74,75,76].

### **Ocean Accumulation of Petro-Plastics**

Packaging materials made from plastics, which amount to a close value of 80 million tons are used in the world at large yearly, plastics pile up in the environment as waste at a rate of about 26 million tons yearly and since plastics do not biodegrade, an appreciable extent of them end up in the oceans [77]. Although pollutants are of very low concentration generally in oceans, but when they adsorb to drifting plastic waste, persistent bio accumulating and toxic contaminants can become concentrated. Bio-based polymer, such as PLA and PHA do not pose the same threat since in most cases are biodegradable or recyclable in nature when compared to conventional which are naturally non-biodegradable.

### **Disposal of Solid Waste**

The problem of solid waste has long been regarded as a global issue couple with human exponential increase in population and with its throw away philosophy. In most cases all this non-degradable plastics are disposed on landfills sites, causing global challenge as effective method of disposing solid waste is not fully available and landfills are becoming rarer in some countries. The replacement of conventional plastics with bio-based plastics will not just bring succour to the devastating issue but will also reduce landfill volume and facilitate the process of composting waste generated from food [78].

## **3.2.2 Economic Issues**

### **Reducing Oil Dependence**

The usage of plastics generally is what has come to stay, and the demand for plastic is not expected to reduce neither is it ready to diminish any time soon. As a result of this unending application for plastics, this would elevate the market value for crude oil if plastics remain highly oil dependent. An approximate of 2% growth per annum is experienced in the consumption of crude oil in recent years, increasing competition has aroused for its usage and it's gradually becoming difficult to find. Any plan to increase the consumption of crude oil will become unsustainable in the absence of significant replacement [79]. Crude oil prices and traditional plastics prices are directly linked, since it's the energy source and raw material engaged in the

production of plastics. The need to reduce oil dependency is essentially crucial and hence the full adoption of bio-based materials is needed to sustain the momentum experienced in the industry.

### **Creating Jobs**

The European Commission (2012a) in *“Innovating for Sustainable Growth: a Bio-economy for Europe”* stated that the European Union’s bio-economy sectors is worth EUR 2 trillion annual turnover which accounted for more than 22 million jobs which represented 9% of the workforce approximately [80]. With appropriate legislative framework and right market conditions the European bio-plastic industry would no doubt offer an immense employment potential. In 2013, the bio-plastic industry created 23,000 employments and could grow to 300,000 high-skilled jobs in 2030. The bio-plastic industry is projected to provide new impetus for development of rural areas in Europe with the new opportunities they present in the agricultural sector, which will promote reindustrialization, and employment growth in Europe [81].

### **Cost of Manufacturing Bio-plastic**

The major problem experienced in the adoption of bio-plastic as an alternative to conventional plastics is cost incurred in its production. Cost incurred in carrying out research and development still makes up for a share of investment in bio-plastic, which has impact on material and product prices. The current low price of oil is making it difficult for bio-plastics to achieve competitive pricing levels with their petro-equivalents. However, continuous decrease in price is imminent with the emergence of companies and brands switching to bio-based plastics. This will expedite the rise in production capacity, supply chains, efficient processes and significant price reduction is bound to happen. Moreover, with massive supply of bio-plastics and growing sensitization of the populace on cost for disposal of petro-based plastics, such awareness strategy would close the gap price differential.

### **3.3 Policy**

#### **Supportive Environment**

With proper implementation of suitable policies, a realistic future development in biotechnology and bio-refining will better the opportunity to start industries and transform existing ones. Consequently, achieving a competitive, broader and supportive environment there is needed to create and maintain a green product and investing in funding fundamental research. Governments in last few decades have developed strategies and frameworks of policies to develop a supportive environment in which bio-economy will thrive. These policies though apply generally to the developments of biochemical, biomaterials and bio-plastics, and also promote bio-based products or the bio-economy as a whole. The policies focus on research and innovation, early market support, and mass market. Organization for Economic Co-operation and Development (OECD) identifies measures and incentives that can be implemented by government, which will affect bio-plastic industries [82]:

- Launching of public recovery systems for bio-waste.
- Simplified special regulations in waste legislation
- Tax legislation
- Agricultural policy measures
- Public funded research and development schemes relating to industry/university projects.
- Well structured campaign covering bio plastic awareness.

#### **3.4 European Union Initiatives on Bio-Plastic**

The EU has set out good policies in fast-tracking the development of innovative technology solutions and aligning industrial objectives with environmental sustainability. Since EU have understood the role of bio-plastic to transit a circular economy and in decoupling economic growth from the depletion of fossil resources. The below are strategies and policy initiatives that are currently in progress for the success of bio-plastic industry in Europe.

- Europe 2020/Innovation Union
- Resource Efficiency Strategy

- Horizon 2020
- Lead Markets Initiative for Bio-based Products
- Bio-economy strategy
- Circular economy package
- Key enabling technologies

The above policies impacts on the development potentials of bio-plastic market are underlisted as follows [83]:

- Solidifying synergies and coherence between European Union and national/regional programmes that support research and innovation relevant to the bio-economy.
- Contributing to the development of conventional standards for bio-based products with regards to bio-based content,
- Supporting knowledge and acquisition and technology exchange, advisory and support services, cooperation and training opportunities among all actors of the supply chain and end-users.
- Improving the accessibility to existing pilot plants and investing into additional infrastructures and activities in order to support the up-scaling of bio-based products and processes.
- Promoting zero-waste campaigns.
- Improving availability and quality information on bio-economy products and processes, and on their socio, economic and environmental impacts, to facilitate informed societal choices.
- Supporting the expansion of new markets by developing standards and standardized sustainability assessment methodologies for bio-based products and products.
- Facilitating green procurement for bio-based products by developing labels, an initial European product information list and specific trainings for public procures.

### **3.5 SWOT Analysis**

In alignment with the research methodology, the SWOT analysis was used as a tool to evaluate the Strengths, Weaknesses, Opportunities and Threat influencing the full adoption of bio-based polyesters as a means of packaging. The essence is to ensure that the realities experience in this industry are well articulated so as to help:

- Maintain and build on discovered strengths
- Take advantage of available opportunities
- Fix or eliminate weaknesses uncovered
- Counter threats as much as possible

#### **STRENGTHS**

- Sustenance of a lower carbon economy
- A catalyst for building competitive bio-based industries.
- An effective means of reducing waste and waste landfills.
- Helps maintain a Greenhouse Gas free environment
- Degradable, recyclable and compostable in nature
- Generated from a renewable sources.
- Will provide the next set of employment/job both skilled and unskilled.
- High awareness of issues related to global warming.
- A whole lot of research is currently on going to help improve the qualities and attributes of bio-based polyesters.
- Big brands and companies (Coca-Cola, PepsiCo, Unilever, Heinz, Tetra Pak, Danone, etc.) involvement in usage of this means of packaging.

#### **WEAKNESS**

- Higher price is a key barrier since research and development stills makes up a share of investment in bio-plastics Industries.
- Food crisis/land required for planting crops used.
- Technology still in its survival phase i.e. technology is not fully matured.

- Environmental policies need to be fully enforced and implemented by government for exponential growth to be experienced in Bio-plastics industries.
- The gap between research advances and commercialized products must be successfully bridged.
- There is need to educate the populace about bio-plastics and its benefits.

## **OPPORTUNITIES**

- Global warming concerns, and aligning with the SDG goals.
- Strong environmental policies in EU concerning global climate change, sustainability and waste disposal options have augmented the enlargement of bio-plastic industries and acceptability of their products.
- The need to maximize the shelf life of packaged foods and drinks.
- Taxation incentives policies and improvement of paybacks for loan invested in this sector.
- Funding for Research and development purposes.
- New improved attributes and qualities of bio-based polyester materials.

## **THREATS**

- Limited raw material supplier for the production of bio-based polyester.
- High capital investment risk due to economic crisis.
- Customer's unwillingness to expend more on purchasing bio-packaged products.

### **3.6 Joint Development/Collaboration Experienced In Bio-Polyester Industry**

1. **Toyobo and Avantium:** In the year 2016, 1<sup>st</sup> of September to be precise, Toyobo Co., Ltd., and Avantium announce their collaboration regarding PEF polymerization and PEF films. Since the announcement, they have come together to develop thin films made from PEF, which is based on Avantium's proprietary YXY technology for the production of FDCA and

it's a 100% bio-based plastic. These PEF films can be applied for food packaging, in electronics applications, industrial and medical packages. These PEF films are about 10 micrometer in thickness which is one hundredth of a millimeter or thereabout. This has facilitated new packaging opportunities such as pouches, which are transparent for sauces, soups or baby foods [84].

2. **BASF and Avantium:** BASF and Avantium, a Dutch technology firm are forming a joint venture company which is focused on polyethylene furanoate (PEF), a bio-based polyester and FDCA (Furandicarboxylic acid) which is its precursor. It is being touted that PEF is a better alternative to polymers such as PET (Polyethylene terephthalate) for food and drink packaging with reasons best ascribed to their superior gas barrier properties. A FDCA plant capable of accommodating up to 50,000 metric tons annually is being planned to be built by the companies. This joint venture gave birth to SYNVINA which produces and markets furandicarboxylic acid (FDCA) from renewable resources on pilot plant scale and markets the new polymer, polyethylenefuranoate (PEF). The company is situated in Amsterdam and operates a pilot plant in Geleen, the Netherlands. Its main aim is to commercialize their activities in the future since FDCA is a building block for various products. Most importantly, PEF is suitable for food and beverage packaging and it provides better performances such as well developed barrier properties and an improved mechanical strength suitable for thinner packaging and it's 100% recyclable. The strength of the company lies in the combination of mother companies' expertise since it's a fusion technology leader with market leaders [85].
3. The European Joint Undertaking on Bio-Based Industries (BBI) is a Public-Private Partnership between the European Union and the Bio-Based industries consortium, which is aimed at enhancing the development regarding investment of sustainable bio-based industry sector in Europe. Its main aim is to ensure European citizen benefit environmentally and socio-economically, increase European competitiveness as well as contributing to the establishment of Europe as a major actor in research, demonstration and deployment of advanced bio-based products and biofuel. In 2017, the European Joint Undertaking on Bio-Based Industries (BBI) granted 25 million Euro to "PEference", a consortium of eleven

companies, which aimed to support the foundation of an innovative process chain for bio-based resources, including chemicals for polyethylenefuranoate (PEF). It also includes the construction of intended 50,000 tons FDCA reference plant, the “PEference” project will be coordinated by SYNINA [85].

The Consortium from raw material producer to brand owner

Among Synina and its shareholders BASF and Avantium, other partners in the PEference consortium are [85]:

- Tereos Participations (France),
- Alpla Werke Alwin Lehner GmbH & Co. Kg (Austria), OMV Machinery Srl (Italy) and Croda Nederland B.V. (The Netherlands),
- Nestec Sa (Switzerland) and Lego Systems As (Denmark)
- Nova-Institut für politische und ökologische Innovation GmbH (Germany) and Spinverse Innovation Management Oy (Finland).

4. **TOTAL AND CORBION:** Total an oil giant from France and Dutch biochemical company Corbion are forming alliance to develop bio-plastics by jointly producing and marketing polylactic (PLA) polymers. Their plan is to erect a state of the art PLA polymerization plant with a production capacity of 75,000 annually, which will be located in Thailand at Corbion’s site which already has a lactide (PLA monomer) production unit that will become part of the joint venture. It is expected that Corbion will do the supply of the lactic acid needed for the production of the PLA and the lactide. The alliance birthed a new company called Total Corbion PLA, which will be located in the Netherlands and operations have since commenced in the first quarter of 2017 [86].

5. **DuPont and Archer Daniels Midland Company:** The two firms reported a new discovery process with the ability to develop the material landscape in the 21<sup>st</sup> century. The bio-plastic precursor can be used for packaging, textiles, engineering plastics and other applications which are high-performance renewable materials. They came up with a method for producing Furan Dicarboxylic Methyl Ester (FDME) from fructose. This discovery has long been in researched, but it is yet to be commercialized due to high cost of production. Nevertheless, the new FDME technology has better efficiency and less complicated process

than conventional conversion process and result in lower capital expenditure, higher output and lower energy consumption. The first produced polymer which is still under development process utilizing FDME is polytrimethylene furandicarboxylate (PTF), it is a novel polyester which is also made from DuPont's proprietary Bio-PDO™ (1,3-propanediol). One of the greatest advantage of PTF is that it is a kind of polymer which is 100-percent recyclable and renewable and when used to make bottles and other beverage packages, it has a better improved gas-barrier properties than other polyesters. The initial step both companies are taking is in the process of promoting FDME's commercialization by advancing on the scale-up phase of the project. [87].

6. **Avantium and ALPLA:** The Dutch firm (Avantium) and ALPLA Werke Alwin Lehner, a leading plastic converter. In May 2013, they made known their partnership agreement for the actualization of PEF bottles and they are part of the few company to collaborate with Avantium proprietary YXY technology. ALPLA has comprehensive knowledge and proven record in PET conversion, bottle design and bottle manufacturing, so it's expedient to say ALPLA will be a key player to facilitate the commercial release, industrialization of PEF, and further ensuring that is in compliance with the technical requirement for the market. ALPLA plans include development of PEF bottles for domestic use and applications [88].
7. **Danone and Avantium:** In the year 2012, Avantium and Danone Research publicized their Joint Agreement for the Development of PEF bottles. It is built on Avantium's YXY technology, and the objective of the two organizations is to contribute to the development of a new environmental friendly material generation whereby the resources will not be dependent on feedstock. This joint agreement paved the way to form another cornerstone of Avantium's marketing strategy to enhance co-development of the YXY technology for producing PEF bottles [89].
8. **Avantium and The Coca-Cola Company (TCCC):** The Coca-Cola Company was the first organization to go in Joint Development Agreement with Avantium which is aimed at the development of PEF bottles. The partnership is a major landmark to smoothen the path to

the commercial production of PEF in the next few years. The Coca-Cola Company is one of the world's largest beverage companies which are consumed at the rate of more than 1.9 billion drinks per day and often times are in single use. Avantium has acquired the Liquid Light, a US company that makes use of waste CO<sub>2</sub> to produce chemicals. With this technology in their possession, the next generation of sustainable Coca-Cola bottles can be successfully produced [90].

9. **Avantium, Mitsui & Co. Ltd. And Wifag-Polytype:** Avantium has also decided to go into partnership with both Mitsui & Co. Ltd. And Wifag-Polytype. Mitsui & Co Ltd. is into the development for PEF thin films in Asia and PEF bottles in Japan, while Wifag-Polytype is a leading manufacturer of thermoforming and printing equipment, and a company that has sole production ranging from sheet extrusion to thermoforming to coating and printing of thermoformed products [89]. With this agreement both Avantium and Mitsui plan to market PEF bottles for 2020 Olympics in Tokyo, since PEF as a packaging material is suitable for oxygen sensitive items used in the food, beverage and health sectors [91].
  
10. **Coca-Cola Company H.J Heinz Company, Nike Inc., Ford Motors Company and Procter & Gamble** cooperatively worked together in 2012, for the acceleration of 100% development of renewable polyethylene terephthalate (PET), a plastic used in manufacturing of packaging materials such as bottles and also for the production of footwear, apparels and automobile fabrics. The collaboration between this industry giants' builds upon the tremendous success recorded from The Coca-Cola Company PlantBottle™ packaging technology which is currently being used for their plastic bottles. The packaging technology employed in making of the PlantBottle™ is partially made from plants and has proven to be environmental friendly [88].

11. **NESTLÉ AND IKEA:** The two companies have entered joint partnership in order to become leading providers of renewable bio-based materials and plastics. The companies also invited others to join their projects in order to utilize their resources in the growing of the market of bio-based products. Nestlé has developed a way of producing renewable plastics identical to the functions of the conventional fossil plastics. The bio-plastic solution will perform as the exact same parameters in production throughout all the various converting steps. The new drop-in bio-plastic can be produced via conventional routes, through the steam cracking of renewable hydrocarbons, produced using the Nestlé proprietary NEXBTL technology. Practically the application for such polymers is endless since they are renewable. This partnership between the two companies covers the manufacture of plastics and other polymer materials using the said solution. The objective of this synergy is to produce plastics similar to presently used ones, while replacing fossil feedstock with renewable, recycled or residual raw materials. Nestlé's objective is to revolutionize the bio-plastic market in the near future to reduce dependency on fossil as well as carbon footprint, while IKEA's objective is to increase the use of plastics manufactured from recycled or renewable raw material [92].

12. **DANONE, NESTLÉ WATERS AND ORIGIN MATERIALS:** This is an alliance between the two world's largest bottling water companies coming together with Origin Materials, a startup situated in Sacramento, California. The three organizations formed NaturALL Bottle Alliance. The aim of the partnership is to develop and launch PET plastic bottle at commercial scale which is produced from bio-based material, i.e. 100% sustainable and renewable resources. Biomass and feedstock such as cardboard and saw dust are used and resources from land are not diverted i.e. food produced for human and animal consumption. This unique approach of Origin Materials was identified differently by the two companies and since then the two companies have synergized to accelerate the development of this promising technology. Both Danone and Nestlé Waters will be providing expertise and team even financial support to help Origin Material make this technology accessible to the entire food and beverage industry in due time. This next generation PET promises to be light in weight, recyclable, transparent and protective of the product. The NaturALL Bottle Alliance partners aim is to ensure everyone benefits from this latest development and makes

the accessibility of the technology easier for the whole beverage industry, such statement therefore shows its willingness to unrestricted innovation and sustainable business [93].

13. **DANIMER AND PEPSICO:** Danimer, one of the world leading biotechnology firm and PepsiCo, a global food and beverage company announced their partnership to developing Danimers' scientific biodegradable film resins which is aimed to meet the sustainable flexible packaging needed for PepsiCo's global food and beverage business. PepsiCo announced its 2025 sustainability agenda in October 2016, this include their commitment to drastically reduce greenhouse gas emissions through all its value chain and in 100% design of its' packaging to be recoverable and recyclable. It is however part of PepsiCo's long decade performance goal and the company also proposed to imbibe initiatives which will deliver top-tier financial performance over a long period of time as well as fusing sustainability into its business strategy. This alliance is expected to help transit PepsiCo into completely biodegradable packaging for their snack food portfolio, with the incorporation of Nodax<sup>TM</sup> PHA bio-plastic into its packaging. Nodax<sup>TM</sup> PHA are biopolymers that occur naturally and are produced by microbial bacteria as they ferment originally sourced oil. This is produced with renewable biomass, so its source is sustainable and has shown ability to replace the usage of many petroleum-based plastics both in terms of price and performance [94].

### **3.7 Current Active Players in the Bio-Polyester Industry**

1. **AVANTIUM:** A Dutch company named Avantium has its focus centered on polyester-furanoate (PEF), an analogue of polyethylene-terephthalate (PET). Avantium was able to raise \$50 million from a syndicate of strategic players in the industry. Amongst the syndicates are The Coca-Cola Company, ALPLA, Danone, Swire Pacific and existing shareholders, follow on investments were also made by existing shareholders Sofinnova Partners, Capricorn Venture Partners, ING Corporate Investments, Aescap Ventures, Navitas capital, Aster Capital and De Hoge Dennen Capital. A joint affirmation was given by all investors as regards the commitment to advance PEF. This raised fund will

be expended on the completion of the industrial preparation of PEF. The development will be based on YXY technology and the set objective of this project is to add to the occurrence of new renewable material, without direct competition with feedstock [95].

2. **SYNVINA:** A joint venture of both Avantium and BASF located in Amsterdam and has an operating pilot plant in Geleen, the Netherlands. The joint venture, Synvina is into the marketing and production of Furandicarboxylic acid (FDCA), which is made from renewable resources on pilot plant scale. Furandicarboxylic acid acts as an integral part for various products and the most significant of the products is polyethylenefuranoate (PEF), which is a suitable material for packaging. The PEFerence project, which was granted 25 million Euros by The European Joint Undertaking on Bio-Based industries will be coordinated by Synvina. The 25million Euro for the PEFerence project was given to a consortium of eleven companies which comprises of representatives from the European Union [85]. An interim approval for recycling polyethylenefuranoate (PEF) was given to Synvina by the European PET Bottle Platform (EPBP) and are expected to operate in the European bottle recycling market. According to EPBP's assessment, the recovery system adopted for polyethylene terephthalate (PET), the traditional material for plastic bottles is expected to be use for the new invention. Amount of PEF to be produced from Synvina's proposed 50,000 tons reference plant for furandicarboxylic acid (FDCA) corresponds with the interim approval given which is 2% market penetration [96].

### **3.8 Analysing Stakeholder's Packaging Goals**

#### **THE COCA-COLA COMPANY (TCCC)**

Packaging to he Coca-Cola Company (TCCC) is seen as a means of protecting their products during the course of delivery before use. This is one of the reasons why TCCC is working assiduously to find ways in alleviating or eliminating non-recyclable packaging. In view of this, TCCC is looking towards efficient optimization of most packaging material used. TCCC plans to encourage the use of renewable resources and they are designing packaging which are resource

efficient and will allow community recycling system. The company's vision is to take advantage of its' significant scale and resources in contributing to an economy whereby reuse of packaging materials is supported [88].

## **PEPSICO**

In 2016, PepsiCo announced its agenda for global sustainability which is centered on furthering its business development so as to respond to changes in consumer and societal needs. Some of the announced sustainable agenda which applied to packaging are; "Reduction of greenhouse gas emissions by at least 20% by 2030 across the company's value chain and cutting down emissions generated from packaging in alignment with collaborators such as suppliers, business partners and customers. One other area of improvement towards sustainability is the design of its packaging to be 100% recoverable or recyclable by 2025 [97].

## **NESTLÉ**

The World's largest food and beverage company is fastidiously assessing the effect of environmental impact on packaging as a fundamental component of its product design. Since the beginning of the 1990s, the company have been cutting down the quantity of packaging being used through its global source reduction programme termed "Nestlé Continuous Excellence" - eliminating unnecessary packaging i.e. promoting zero waste and reducing weight while ensuring the product quality is not compromised. They have since reduced their packaging weight and have replaced non-recyclable plastics with recyclables ones [98].

## **DANONE**

Packaging is imperative to protecting food and reducing food waste, but packaging itself uses raw material that can generate waste when not recycled. In a bid to promote a sustainable lifestyle there is need to tackle this negative impact. The company's strategy is to promote the use of sustainable materials derived from sustainable resources and seeing waste handling from another perspective such as a new valuable resource innovation. The company's R&D team is working in other to ensure that 100% of packaging used is fully recyclable. By 2020, the company aims to put an end to the use of paper-based packaging obtained from unsustainable

resources e.g. deforested areas. They are dedicated to the bio-economy, which is the use of bio-sourced plastic materials and also aim at creating a second life for all plastics used in the country [93].

## **UNILEVER**

Unilever, a consumer packaging goods company is taking a bold step towards more sustainable plastic packaging. The company announced their commitments to ensure that all of their plastic packaging is fully reusable, recyclable or compostable by 2025.

For a smooth transition to global plastic packaging material, Unilever has committed to;

- “Ensure all of its plastic packaging is designed to be reusable, recyclable or compostable by 2025.
- Invest in proving, and then sharing with the industry, a technical solution to recycle multi-layered sachets, particularly for coastal areas which are most at risk of plastics leaking into the ocean.
- Renew its membership of the Ellen MacArthur Foundation for another three years and endorse and support their New Plastics Economy initiative. As part of this, it will publish their full “palette” of plastics material used in its packaging by 2020 to help create a plastics protocol for the industry” [99].

## **HEINZ**

The H.J. Heinz Co. is on the path to reducing greenhouse gas emissions, solid waste, water consumption and energy consumption by 20% by 2015 and is on the right direction to achieving or surpassing their set environmental targets. In 2012, Heinz reiterates its commitment to environment during the celebration of Earth day. The company adopted the plastic bottle which is made up to 30% plant-based. This was made possible as a result of their strategic partnership with The Coca-Cola Company [100].

## **TETRA PAK**

Jason Pelz, the VP of the company on environment for US and Canada says the act of recycling is currently one of the effective methods in promoting sustainability. The company plans to reduce greenhouse gas emission by 40% by 2030 and made the availability of renewable energy sources possible on site. The company is also working on replacing fossil based plastics with bio-based plastics for a greener packaging concept. According to an update in 2012, the company recycled around 23% of carton packages sold in 2012, which showed an increase when compared to the 21% recorded in 2011 [101].

**Table 6.** Renewable chemicals (companies and their products) [85]

COMPANY	PRODUCT
AVANTIUM	Alkoxyethyl-furfural; Furandicarboxylic Acid (FCDA); Methyl Levulinate; Mono-Ethylene-Glycol (MEG)
BASF ENZYMES LLC	1,4-Butanediol (1,4-BDO); Enzymes; Polytetrahydrofuran (PolyTHF®)
BIORESOURCE INTERNATIONAL INC	Enzymes
BRASKEM	Butadiene; Ethanol; Ethylene; Isoprene; Propylene; Polyethylene; Polypropylene
CARGILL	Citric Acid; Ethanol; Glucaric Acid; Glycerin; 3-Hydroxypropionic Acid; Isoprene; Lactic Acid; Itaconic Acid; Lecithins; Maltodextrins; Palm Oils; Polyols; Sorbitol; Sugars; Starches; Triglycerides; Xanthan Gum
CORBION	2,5-Furandicarboxylic Acid (FDCA); Lactic Acid; Polylactic Acid (PLA); Succinic Acid
DUPONT	Enzymes; 2,5-Furandicarboxylic Acid (FDCA); Isoprene; polyester
GEVO	Iso-Butanol; Butene; Ethanol; Isooctane; p-Xylene
GLOBAL BIOENERGIES	Butadiene; Isobutene; Propylene
MERIDIAN BIOPLASTICS	Medium Chain Length Polyhydroxyalkanoates (MCL-PHA)
MYRIANT CORPORATION	Acrylic Acid; Fumaric Acid; Lactic Acid; Muconic Acid; Succinic Acid
NATUREWORKS, LLC	Polylactic Acid (PLA)
NOVOMER	Acrylic Acid; Butanediol; Polypropylene Carbonate Polyols; Succinic Acid
THE COCA-COLA	Polyethylene Terephthalate (PET), PlantBottle™
THE DOW CHEMICAL COMPANY	Ethanol; Plasticizers; Polyols
VIRENT	Aromatic mixtures; Benzene; p-Xylene

## 4 SUMMARY

This section draws its conclusion based on the SWOT analysis and the outcome of market research on bio-based polyesters. Based on the research conducted, it is conspicuous that the role of bio-based polyester on food and drink packaging can not be over emphasized, as its impact is immense. Though the bio-plastic industry is projected to increase exponentially in production capacity by 2020 since the populace are becoming more aware of the impact of depending on packaging materials based on fossil fuel, the need to reduce the emission of CO<sub>2</sub>, dependability on fossil fuel usage, carbon footprint of packaging, greenhouse gases, ability to offer more recycling and recovery options, and sustenance of a good ecosystem are few out of numerous reasons why Bio-plastic industries are receiving this much acceptance at large.

However, the bio-plastic industry is perceived to be young, since it represents a fraction out of tons of plastics produced worldwide annually even though it has an enormous yet unutilized potential. For full environmental, economic and social potentials to be actualized in this sector, the government must help implement policies and frameworks to guarantee access to competitively priced agricultural feedstock and biomass in sufficient quantities and qualities, invest massively in research and development, provide political support through supportive market mechanism aimed at encouraging a market shift towards increased production and use of bio-based packaging, help sensitize the populace about the importance of a transition to a bio-based economy and its benefits, provide subsidy, reduce taxation and boost incentives, promote zero-waste campaigns and help promote knowledge acquisition in this field. These policies when implemented will serve as a means of overcoming the major threat (high price) being experienced in the industry and will further expedite the development of the bio-plastic industry hence, exponential growth soon will be the order of the day.

Moreover, with the synergy being experienced within big brands such as Avantium, Coca-Cola, Danone and ALPLA towards full commercialization of PEF which is 100% bio-based, all renewable and recyclable. It is expedient to assert that bio-based polyesters will thrive drastically if the aforementioned challenges are being surmounted. In ratification, bio-based polyester is a packaging means to reckon with couple with their immeasurable attributes and qualities, which

make them stand out in packaging of foods and drinks, but will require government participation to actualize its full course.

## 5 CONCLUSIONS

This research study can firmly say that the usage of bio-based polyester as a packaging means is not yet matured as it is still in its early phase but usage of this means of packaging is advantageous both in sustainability of shelf life and environment. In respect to the market report by European bioplastics in collaboration with nova institute in 2016, the bioplastics market is expected to receive an upsurge in the packaging sector in the next five years. Moreover, joint development is being experienced at different segments in the industry and the most recent is the partnership between Avantium, Coca-Cola, Danone, Swire Pacific, and ALPLA. With this synergy Avantium have been able to raise over \$50 million from a consortium of those aforementioned and which will be channelled into the advancing of PEF, the next generation packaging material. Indeed one can categorically say that if more of this partnerships or synergies are being experienced then bio-based polyesters soon enough will dominate as the leading packaging materials.

Although the low penetration of bio-based polyester experienced in the market is as a result of total cost incurred in production, fall in price of crude oil which serves as the major component in conventional packaging, also cost incurred on carrying out research and development in bio-plastic industries. All this makes up to the reason why bio-based polyester is not as cost effective when compared to conventional packaging which in turn has an effect on its market penetration but with enactment of proper frameworks and appropriate policies by the government in areas of tax reduction, increment of incentives, provision of funds for research and development, procurements, sensitization of the populace on the importance of transitioning to bio-based polyesters, promotion of waste avoidance campaigns and seminars the bio-plastic industry will experience a new dawn and hence a swift nosedive will be experienced in pricing areas.

Finally, it is appropriate to conclude that bio-based polyesters and bio-plastic industries have come to stay, but their success in the market is dependent on the intervention of the government.

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