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Exploration of Bioplastics: (A Review)

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ABSTRACT

The marvellous and versatile properties of synthetic plastics make them an indispensable part of human lives. But in the recent years, plastic pollution has become the biggest environmental concern for the whole world globally. Environmental distress over plastic pollution associated with a rising debate over fossil fuel dependence and abatement have brought the attention of researchers towards finding a suitable alternative to plastics i.e., bioplastic. Bioplastics are specially designed to have lower carbon footprint, less dependent on natural resources, energy efficiency, environmental safety and sustainability. These are bio-resources based polymers which have the potential of substituting conventional petroleum-based plastics. This review article summarizes need for developing eco-friendly alternative to plastics, bioplastics, importance of bioplastic, advantages of bioplastics over plastics and current trends in production of bioplastics. It also highlights types of bioplastics based on various sources and a variety of bioplastic materials such as starch, cellulose, chitosan, chitin, polyhydroxyalkanoates, polylactic acid, Bio-PE, Bio-PET, Bio-PBS, etc., their synthesis, applications and biodegradability. A comparative analysis of both natural and bio-based polymers in term of their availability, nature, structure, properties such as thermal stability, biodegradability, tensile strength, etc. has also been highlighted.

Keywords: Bioplastics, Eco-safety, Energy efficiency, Natural resources, Sustainability.

INTRODUCTION

"Plastics" as synthetic polymers were proposed almost hundred years ago and nowadays these are the highest produced, used, widely available and most dynamic materials[1-3]. Plastics find a significant role in almost every place in our daily life ranging from food packaging, pharmaceutical and communication technology to technical applications such as electronics and automobiles[4-11]. Plastics are very useful as synthetic polymer due to various properties. The structure of plastics can be chemically altered to various shapes and strengths to produce higher molecular weight, less reactive, highly durable and non-biodegradable products[12-17]. Due to their versatile properties, plastic production has increased substantially in 2020 by almost 36% since 2010[18].

Need for developing eco-friendly alternative to plastics

Even though plastics have a lot of advantages but certain disadvantages also. Most of plastics are derived from fossil resources and these are non-renewable and limited in nature. Due to excessive production of plastic and its products, these natural resources are depleting at a very fast rate. Apart from those plastics decay very slowly which can cause the plastic products to persist in the landfills for hundreds or even thousands of years which led to environmental pollution[19-29]. Plastic waste has become a global challenge[30]. Nearly half of the polymers developed by man end in one-way or short-lived products, which mostly accumulates in solid waste landfills, fresh water bodies and in the oceans, where they get degraded into 'microplastics' over time and prove harmful to marine organisms and lastly end up on our plates[31-35]. Plastics remain suspended on the surface of almost every ocean of the world. One of the notable example of this plastic accumulation zone is The Great Pacific Garbage Patch that is located between Hawaii and California. Almost 94 79,000 tonnes of plastic waste is piled up in this area of 1.6 km^2. About 8% of this plastic waste is present in the form of microplastics and the remaining is present as floating form of plastic[36].

Synthetic plastic such as polystyrene, polyethylene, poly vinyl chloride, etc. derived from non-renewable petrochemical resources release greenhouse gases such methane, carbon monoxide, nitric oxide, etc. which eventually has an immense effect on increasing global warming[37,38]. On a global trend, both production of plastic from petro-based sources and incineration of plastic waste account to about 400 million tonnes of carbon dioxide every year[39]. Burning of these plastic products also emits toxic substances which prove to be hazardous to the environment and also to the human beings as these toxins cause respiratory diseases and many more health issues[40].

Seeing all the issues, we can say that plastic pollution affects environment at all levels right from its synthesis to discarding and incineration[41-44]. No doubt, plastic products contribute largely in the development nowadays, but this development is possible only when we concern about the wellbeing of the environment. And that is the reason, there is augmenting interest in uncovering the materials which have alike properties as those of petro-based plastics[45].

Further, degrading environment, depletion of natural resources, rising prices of fossil fuels and problem of waste disposal have also paved the way of research towards eco-friendly alternative to plastics[46-59]. This eco-friendly alternative is Bioplastic[60,61].

The synthesis and use of bioplastics is considered as more sustainable activity in comparison to production of plastics which further opens up opportunities to overcome depletion of natural resources and environmental hazards caused by plastics[62-72].

Bioplastics

According to European Bioplastics, a plastic material is said to be bioplastic if it is either bio-based or biodegradable or possess both the properties[73]. International Union of Pure and Applied Chemistry (IUPAC) has defined bioplastic in the following way, "a bioplastic is derived from biomass or monomers derived from biomass and which, at some stage in its processing into finished products, can be shaped by flow"[74].

Bioplastics are derived from organic materials found in nature such as polysaccharides, lipids and proteins. Different polysaccharides used for synthesis of bioplastics are cellulose, starch, lignin, chitin, dextrin, pectin, gum, etc. Casein, gelatin and gluten, and animal fats and plant oils are the naturally occurring proteins and lipids respectively of from which bioplastic is obtained[75-81].

Latest advancements are evolving to expand bioplastic production from plant based renewable waste substances, biomass, microbial and microalgal cells so that there is no competition with agricultural and food resources. These sources of bioplastic are obtained mainly from organic wastes generated from food waste, corn and sugarcane waste, vegetable waste, agricultural waste, household kitchen waste, by-products of wood industries, etc[82].

Utility of greenhouse gases such as carbon dioxide for synthesis of bioplastic is also one of the most sustainable carbon upcycling perspectives that is attaining an enormous recognition now-a-day[83]. It will eventually promote minimal carbon footprint for the production of bioplastics[84].

Now-a-days researchers and scientists also focus on designing novel bio-composites which are comprised only of bio-based materials having preferred functionalities and properties that are apt for various technological applications[85-87]. Blending of different bio-based polymers is also in trend to enhance their versatility and efficiency in terms of biodegradability and recyclability[88].

Advancements in industrial biotechnology propose numerous synthetic routes such as bio-catalytic transformation and chemo-enzymatic catalysis for developing varied monomers and polymers which are bio-based and derived from biomass and renewable feedstocks[89-91].

The biodegradable plastics disintegrate into water, carbon dioxide, humus, biomass, and different other natural substances which are not harmful for the environment.

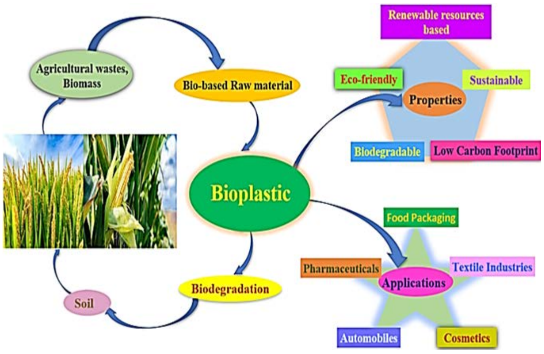

Fig. 1. Bioplastic: Recycling, Properties and Applications

Importance of bioplastics

These bioplastics comprising of both naturally and chemically derived substances from natural and renewable resources are being planned to exhibit[46,76,92,93]:

- Complete biodegradability,
- Decrease toxicity,
- Lower carbon footprint,
- High recyclability,
- Sustainability and
- Environment-friendliness

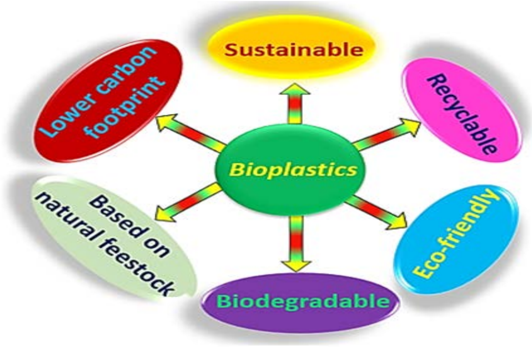

Fig. 2. Importance of Bioplastics

These bioplastics have replaced petro-based conventional plastics and are extensively used for various industrial and environmental applications[94].

Advantages of Bioplastics over plastics[95-98]

The bioplastics show various kinds of advantages over the conventional petroleum-based plastics.

Table 1: Advantages of Bioplastics over Plastics

	Bioplastics	Conventional Plastics
Sources	Partly based on renewable sources (natural feedstock)	Based on non-renewable sources (petrochemical sources)
Carbon Footprint	Comparatively lower	Much higher
Energy Efficiency	Production requires less energy	Production requires more energy
Eco-safety	More environmental-friendly	Causes environmental pollution
Biodegradability	Either completely or partly biodegradable	Mostly non-biodegradable

Various terms

Degradation-The process in which a polymer breaks down into smaller particles by the action of certain abiotic factors such as sunlight (UV radiations), air, or through any microbial process. Polyethylenes are the most common type of degradable plastics.

Biodegradation-The process of decomposition of a polymer into tiny fragments through biological activities and carbon dioxide, methane and water are formed as a outcome of biodegradation.

Bio-based plastics-The plastics that are either biodegradable or bio-based i.e. they are derived from naturally available resources or biomass in some way or the other. For example, Bio PE, Bio PVC, etc.

Compostable Plastics-The plastics that undergo biological decomposition in compost sites forming water, biomass, carbon dioxide and other inorganic compounds without leaving any harmful materials in the environment[99].

Conventional Plastics-The plastics that are based on petro-products i.e. derived from fossil fuels[100].

Current Trends in production of Bioplastics

At present, bioplastic materials contribute about one percent to total plastic production but the market is expanding continuously. In 2021, the global production scope of bioplastics was around 2.42 million tonnes, which is estimated to increase to approximately 7.49 million tonnes by 2026.

Around 64% of all the bioplastic materials synthesized are biodegradable which includes PBAT (polybutylene adipate terephthalate), PLA (polylactic acid), PHA (polyhydroxy alkanoates), PBS (polybutylene succinate), starch blends and others. Among them, PBAT contributes approximately 19.2% of the total global production of biodegradable bioplastics. Mainly PLA about (18.9%), starch blends (16.3%), other biodegradable plastics (10%) including PHAs (1.8%) and PBS (3.5%) are synthesized on industrial scale.

Bio-based and non-biodegradable plastics contribute to around 36% to the total global production of bioplastics. Majority of them include bio-based PET (polyethylene terephthalate), bio-based PE (polyethylene), bio-based PA (polyamides) and PEF (polyethylene furanoate), a new biopolymer that is anticipated to enter the market in 2023[101].

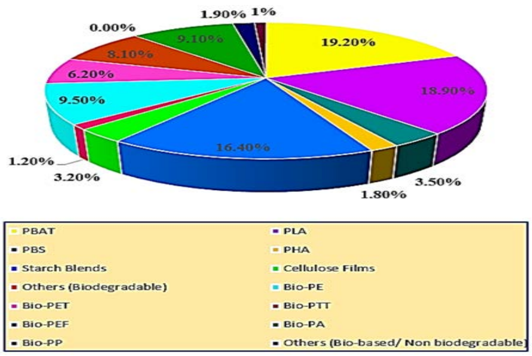

Fig. 3. Worldwide production capacity of bioplastics in year 2021 (data adapted from European Bioplastics)[101]

Types of Bioplastics

These biopolymeric materials are distinguished on the basis of their origin; natural and synthetic. Natural bioplastics are formed as a result of continuous evolution in nature while synthetic bioplastics are produced through significant research and progress in this field. Both these processes result in emergence of materials possessing characteristics for varied applications[102].

Natural bioplastics can further be classified into three types based on their sources of production which include production from biomass resources (polysaccharides, polypeptides, lipids), from microorganisms (polyhydroxybutyrate, polyhydroxyalkanoates) and from biotechnological applications (polylactide, poly lactic acid). Synthetic bioplastics can be divided into three categories namely aliphatic polyesters (polycaprolactone), aliphatic copolyesters (polybutylene succinate) and aromatic copolyesters (polybutyrate adipate terphthalate)[103].

Considering the comprehensive properties of both natural and synthetic biopolymers, they both accomplish a pervasive and vital role in every sphere of life. These biodegradable polymers reveal the occurrence of biodegradation by having a period of fruitfulness.

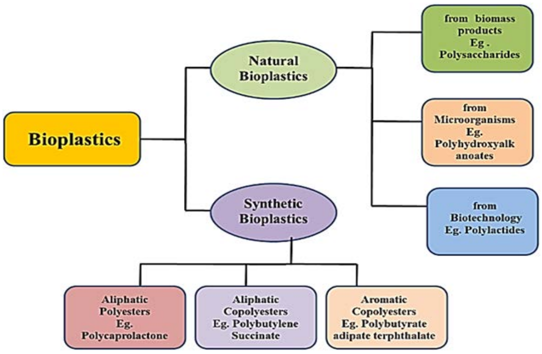

Fig. 4. Bioplastics based on different resources and production methods

Bio-based Natural polymers

Bioplastic derivatives obtained from different natural resources like cellulose, starch, chitin, chitosan, etc. have allured substantial attention of researchers to replace the typical petro-based plastics[104-106]. These naturally existing polymers and their blends stand at highest as far as production capacity of bio-based polymers is considered worldwide[107,108].

Starch

Starch is the naturally occurring polysaccharide and amplest biopolymer available on the earth. It is the vital carbohydrate product of plants that is stored for energy. Starch is obtained from a variety of sources such as potatoes, rice, maize, wheat, etc[109].

It contains a huge number of glucose units associated by 1,4- and 1,6-gycosydic linkages which results in formation of two types of units:

- Amylose (linear and helical structures)
- Amylopectin (branched structure)

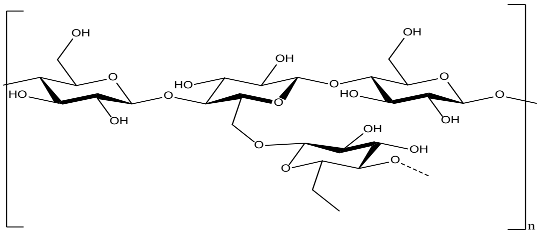

Fig. 5. Structure of Starch

The ratio of amylose/amylopectin has a great impact on the characteristics of starch[110]. Due to the significant utility of starch including appreciable availability, renewability, cost effectiveness and biodegradability, it has been looked upon as a promising substitute material for synthesizing bio-based polymers[111-118].

There are strong intermolecular and intramolecular hydrogen bonds among starch polymers which makes it highly crystalline in nature. Due to this, it has a very high melting temperature which is near to degradation temperature and this hinders the way of melting during synthesis of starch films. Hence starch is modified using physical and chemical processes during production of bioplastic.[119-121].

There are many ways in which starch can be utilized as biopolymer. First, important chemicals like organic acids and ethanol can be produced from starch. Second, it can serve as a filling material to plastics. Third, through modification of starch[122,123]. Mostly starch is blended with thermoplastic polymers and plasticizers and thermoplastic starch is obtained which is biodegradable and has varied applications. The linear structure of amylose in starch favours the development of bioplastics which are stronger and have highly adjustable mechanical and physical properties. In contrast, the branched structure of amylopectin leads to production of bioplastics which have low resistance to tensile strength and elongation[124]. Starch is mainly modified with other materials to exhibit desired properties. Novamont is the most active and major producer of starch-based products in the market[125,126].

Starch and transformed starches possess a wide array of applicability in the production of films for shopping, fishing bait bags, packing materials, food packaging, special mulch films, packaging foam and injection-molded materials, for example, ‘take away’ food containers. Further useful areas of starch applications are textiles, construction, pharmaceuticals, cosmetics, paints, paper and cardboard industries[127].

In certain thermoplastic starches, brittleness arises due to increase in crystallinity, brittleness also increases over time. In future starch can be employed as a natural and renewable substrate for the synthesis of many biopolymers[46].

Cellulose

Cellulose is the foremost constituent of cell walls of almost all plants and a rigid polysaccharide. It is comprised of a large number of monosaccharide units of β-glucose joined in linear fashion. Common sources of making materials for the synthesis of cellulosic plastics are wood and cotton fibres. Plant fibres are dissolved in carbon disulphide and alkalis to form viscose, from which rayon (fibre) or cellophane (film) can be obtained in a bath of sodium sulfate and sulfuric acid[46].

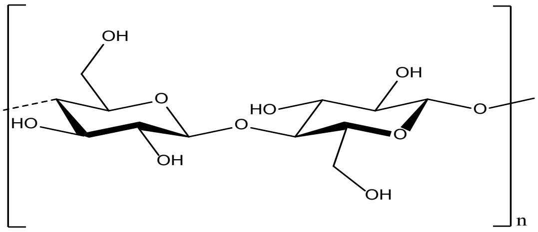

Fig. 6. Structure of Cellulose

Cellulose has high tensile strength and it is a stiff polymer. Because of high abundance, cellulose can be served as a renewable source of substrate for the synthesis of sustainable bioplastic materials[128,129]. The important derivatives of cellulose that have industrial uses are cellulose esters, cellulose acetate and regenerated cellulose for fibres[129]. Eastman Chemical is one of the chief producer of cellulosic plastics[46].

Due to the structural compatibility of cellulose, it forms hydrogels which found utility in scaffolds of cell culture, tissue engineering, bone implantation, modelling of cartilage, drug delivery, absorbance of heavy metals, retaining of soil water, effective release of fertilizers for agricultural purposes[130].

Cellulose ethers have applications in food, pharmaceuticals, personal care, paint and construction activities. Cellulose esters are widely used for producing films and fibres. Regenerated cellulose fibres are mainly utilized in textiles, disposables items for hygiene and home furnishing fabrics due to their high thermal stability[131,132].

Chitosan and Chitin

Chitosan and Chitin are amplest natural amino polysaccharides and precious bio-resources based natural polymers. After cellulose, chitin is the second most plentiful agro-polymer found in nature. Chitin is a long chain polymer of N-acetylglucosamine. It is present in the exoskeleton of arthropods, cell walls of yeasts and fungi in the form of crystalline microfibrils that constitute their structural components[133]. Chitin is non-toxic, bio-compactible and biodegradable in nature[134]. These are commercially produced from prawn, crab and shrimp wastes through chemical extraction processes[135,136].

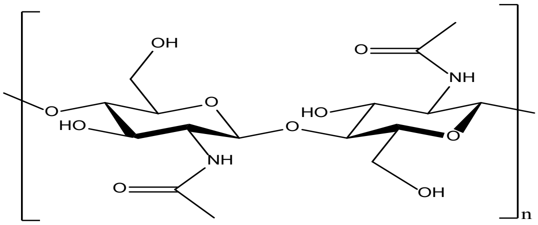

Fig. 7(a). Structure of Chitin

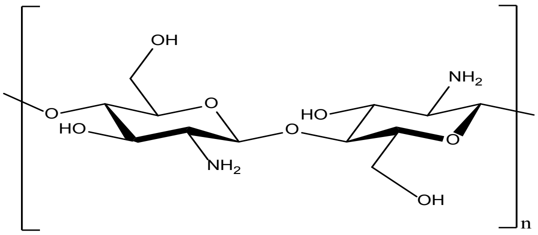

Fig. 7(b). Structure of Chitosan

Chitosan is produced from chitin by deacetylation of chitin. Chitosan has many distinguishable features which include chemical inertness, biodegradability, high mechanical strength, biocompatibility, bioactivity, high mechanical strength, low toxicity, low cost and good film-forming properties[137-139]. Based on different properties it has a vast area of applications in pharmaceuticals, cosmetics, plant protection, water treatment, medical devices, skin care industry[140-144].

Bio-based polymers

Polylactic Acid (PLA)

It is a bio-based and biodegradable polymer. It has a monomeric unit, Lactic acid which is produced either by micro-organism catalysed fermentation of simple carbohydrates or by chemical processes[145].

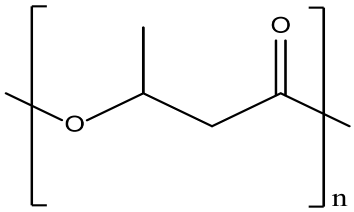

Fig. 8. Structure of PLA

On a global platform, PLA is receiving greater attention from both academia and industries because of technological advances in its production process and functionality[146]. The active companies in this field are Nature Works, Teijin, Total Corbion, and Purac which mainly utilize lactic acid fermentation process instead of chemical synthesis[147]. The most common raw materials used in this process are corn starch, cassava roots, sugarcane and potatoes as the source of carbohydrates which accounts for the industrial process of lactic acid synthesis renewable and sustainable[148].

PLA as bio-based polymer has many amazing characteristics such as glossy appearance, efficiency to withstand different processing conditions, ability to act as a barrier, good transparency & very high rigidity[149].

Polylactic acid is one of the major productive biopolymers that yield 1 kilogram of product from 1.6 kilogram of the fermented carbohydrate source. PLA has greater utility in food-packing industry (for the production of bottles, cups, foil, moulds, etc.), textile industry, cosmetics and pharmaceutical industry, electronics and automotive industry and in 3D printings[127,148]. Now-a-days blends of PLA with other polymers are also utilized to intensify its functional and biodegradable properties so as to have advance packaging applications[150].

But the major drawback of PLA is that it is not heat resistant and cannot withstand high temperatures. High brittleness, low toughness and slow biodegradation are also some of the problems associated with PLA which further hamper its specific applications. Research is being done to develop PLA as more eco-friendly and to make it heat resistant[151].

Polyhydroxy Alkanoates (PHAs)

PHAs are a broad group of biodegradable polymers, but mainly refer to poly (3-hydroxy butyrate) and its copolymer (poly (3-hydroxy butyrate-co-3-hydroxy valerate)).

On the basis of carbon chain length of the monomers, PHAs are grouped into two major categories:

- Short chain length 3-3-hydroxyalkanoates (scl-3HA) with 3-5 carbon atoms
- Medium chain length-3-hydroxyalkanoates (mcl-3HA) having 6-16 carbon atoms[152].

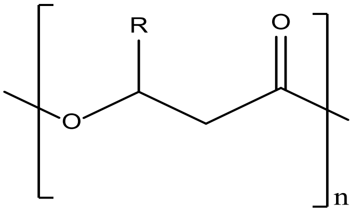

Fig. 9. Structure of PHA

Metabolix is the main leading company in the production of PHAs. A large number of patents associated with PHA shows that it is used extensively as a biodegradable polymer[153].

These polyoxoesters are synthesized by bacteria through anaerobic digestion of lipids or sugars via polyhydroxy fatty acids. Polyhydroxy alkanoates (PHAs) are produced in bacterial cells as energy storage product. These are separated from bacterial cells through centrifugation, filtration and solvent extraction. Food and agricultural wastes such as mango peel, potato peel, wheat bran, rice husk, straw, etc. are also utilized in the production of PHAs.

Main properties of PHAs are[154]:

- Completely biodegradable in water, soil and compost
- Highly resistant to oil and grease
- Good printability
- High thermal stability (can withstand temperatures nearly upto 180̂ C)
- Non toxicity
- Biocompatibility
- Resistance to hydrolytic degradation

PHAs are mostly used in packaging, disposable cups, disposable razors, shampoo bottles, surgical pins, surgical stitches, disposable knives and forks, injection molding grades and woven medical patches[126]. With a greater area of applications, the issues that hinder the commercialization of PHAs are slow crystallization rate, brittleness, narrow processing window and sensitivity to thermal degradation[155].

Biocompatibility and mechanical features of PHAs can be altered by adjusting the surface, blending or integrating with different enzymes, polymers and inorganic substances, which further allows a vast range of applications[156,157].

Polybutylene succinate (PBS)

PBS is a biodegradable and aliphatic polymer which is prepared by condensation between 1,4-butanediol and succinic acid. It is synthesized either by monomers produced from fossil-based sources or by fermentation through bacteria. Nowadays, products of 100% bio-PBS are available in the market. Bio-PBS is prepared from bio-succinic acid and bio-ethanol which can be obtained from sugarcane and cassava monomers[158].

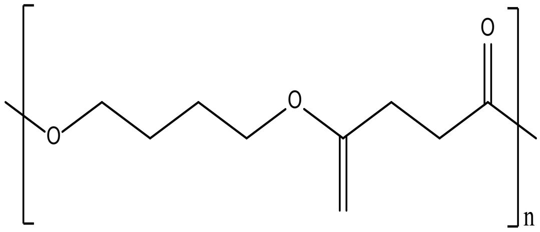

Fig. 10. Structure of Bio-PBS

The route through fermentation is more advantageous as it utilizes renewable resources and energy efficient as compared to chemical process. This bio-based process of synthesis involves utilization of glucose to produce succinic acid and 1,4-butanediol from natural and renewable resources[159].

PBS is a semi-crystalline polymer and its thermal and mechanical characteristics depend on the degree of crystallinity and structure of the crystal[160]. PBS has high flexibility, heat resistance, natural fibre compatibility and biodegradability. It has good impact strength and tensile strength along with moderate hardness and rigidity. Due to these properties, they have vast area of applications in industries such as pharmaceutical, agricultural, packaging, textile, electronics and electrical sand automobiles. It is also used for manufacturing plastic utensils, plates, bowls, etc[161].

The comparatively poor mechanical variability limits the applications of 100% bio-PBS products. So, it has to be copolymerized with certain other polymers for improving its strength and properties[158].

Bio-polyethylene (Bio-PE)

PE is made up of long chain polymers of ethylene which is synthesized as either HDPE (High Density Polyethylene) or LDPE (Low Density Polyethylene) or LLDPE (Linear Low-Density Polyethylene). In chemical industries, PE is produced by polymerization of ethane[162].

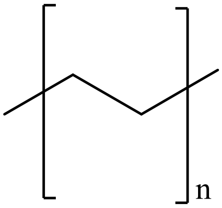

Fig. 11. Structure of Bio-PE

Bio-PE has similar physical, chemical, technical and mechanical properties to polyethylene[163]. Ethanol synthesized by microbial fermentation is used in preparing green polyethylene. The production of bio-ethanol utilizes renewable resources such as sugarcane, starch crops including wheat, corn, maize, etc. and other plant wastes[164,165]. Bio-PE is used to obtain valuable products by considering eco-friendly methods and hence contributes towards sustainable environment. Brazil's Braskem company is one of the world's chief producer of bio-PE[166].

HDPE is the most widely used copolymer of bio-PE due to its significant properties. It has close packed polymer chains which results in strong intermolecular forces that enhance its rigidity and crystallinity. It is highly tough polymer and has good thermal resistance and can bear high temperatures upto 120°C, without having any effect on properties of the material. HDPE is inert to many chemicals, oils, acids, bases, aldehydes, alcohols and esters. Bio-PE has good performance and is also cost effective. It is extensively used in packaging (food packaging which involves packaging of water bottles, milk and plastic bags, carrying bags, plastic bottles and films), personal care, healthcare, laboratory objects, cosmetics, toys, engineering, automotive parts, agriculture and many day-to-day essential commodities.

Even though it has widespread applications in almost all areas but the major disadvantage is that it is non-biodegradable. Because of this it persists in the environment for several hundred years. Attempts are being made to recycle Bio-PE to resolve the problem of non-biodegradability[46].

Bio-polyethlene terephthalate (Bio-PET)

PET is a polyester polymer. The monomer of PET, ethylene terephthalate (bis(2-hydroxyethyl) terephthalate) is prepared by esterification reaction between ethylene glycol and terephthalic acid. It generally contains 30% ethylene glycol (EG) and 70% terephthalic acid (TPA). Bio-PET contains the renewable monomer i.e., monoethylene glycol (MEG). MEG is obtained from sugarcane-derived ethylene. These monomers are derived from fermentation of glucose[167]. Researchers have also developed feasible process to synthesize bio-based TPA by utilizing n-butanol, isobutanol, isobutylene, limonene, muconic acid, carbohydrates (fructose and glucose) and terpenes, as substrates[168].

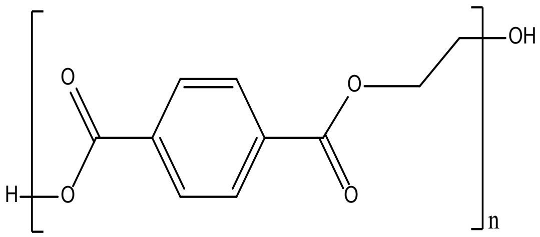

Fig. 12. Structure of Bio-PET

The potential of Bio-PET packaging is similar to other petro-based PET products[169]. It has excellent thermal properties. It can act as a good barrier agent[170].

Bio-PET is assisted by Coca Cola by the name 'Plantbottle'. Sprite, Dasani, and Fresca also use similar packaging for bottles[171]. Pepsi has also announced 100% renewable PET material synthesized from pine bark, switchgrass and corn husks. It is mainly used as packing material for bottles. It can be degraded by bacteria Nocardia with its esterase enzyme[172-174].

Comparative Analysis of different types of Bioplastics

The bioplastics vary in accordance to their availability, nature, structure, properties such as thermal stability, biodegradability, tensile strength, etc. A comparative analysis of both natural and bio-based polymers has been done in the following tables.

Table 2: Comparative Analysis of Natural Polymers

	Starch	Cellulose	Chitin	Chitosan
Source	Stored in plants as their food	Found in cell wall of plants	Exoskeleton of arthropods, cell walls of yeasts and fungi	Chitin
Structural Unit	α-glucose	β-glucose	N-acetylglucosamine	N-glucosamine and N-acetylglucosamine
Nature	Occurs naturally	Occurs naturally	Occurs naturally	Obtained by deacetylation of Chitin
Biodegradability	Yes	Yes	Yes	Yes
Thermal Stability	Good	High	High	Good
Tensile Strength	Good	High	High	Low to high
Toxicity	Non toxic	Non toxic	Non toxic	Non toxic
Colour	White	White	Yellow-white	Yellow
Renewability	Yes	Yes	Yes	Yes

Table 3: Comparative Analysis of Bio-Based Polymers

	PLA	PHA	Bio-PBS	Bio-PE	Bio-PET
Source	Corn starch, cassava roots, sugarcane and potatoes as the source of carbohydrates	Bacteria	Sugarcane and cassava monomers	Bio-ethanol obtained from glucose	Glucose and cellulose biomass
Structural Unit	Lactic acid	Hydroxy alkanoates	Succinic acid and 1,4-butanediol	Ethylene	Ethylene glycol and terephthalic acid
Nature	Synthesized	Synthesized	Synthesized	Synthesized	Synthesized
Biodegradability	Yes but slow	Yes	Yes	No	May or may not be
Thermal Stability	Low to Medium	Low to Medium	High	Medium	High
Tensile Strength	Good	Good	Good	Good	High

Future scope

The area of exploration for biopolymers is significantly expanding because of its biodegradability and sustainability. Bioplastics is a wide-ranging family of materials with extensively diversified properties. Bioplastic products have a vast area of applicability from day-to-day essential commodities to advance technological applications.

But economy scale including management of bio-based raw materials, conduct of the raw materials and their cost of manufacturing are some of the challenges that need to be addressed in near future.

To design these processes economically accessible, it is very essential to evolve:

- Logistics for renewable feedstocks,
- Novel synthetic approaches by restoring existing techniques with enhanced yields,
- Novel strains of microbes and enzymes and
- Effective ways for the recycling of bio-based raw materials.

Innovations in elementary reforming of bioplastics with enhanced economies aimed to recycling will open up new opportunities in the area of development of sustainable bioplastics.

CONCLUSION

Alarming rate of environmental pollution caused by synthetic polymers made the search necessary for developing sustainable and cost-effective alternatives. In this series, emergence of bioplastics has become a novel and an innovative field of research for scientists all over the world. Bioplastics act as eco- friendly, highly biodegradable and cost-efficient alternatives to the conventional petro-based plastics. A rational design of bioplastics to bestow specific and desired properties such as functionality, biodegradability, recyclability and utilization of unaccounted biomass as a precious and renewable resource would together manifest a sustainable and greener approach towards production and effective applications of bioplastics.

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Conflicts of Interest

The authors declare no conflict of interest.

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