Recent Advances in Bioplastics: Synthesis and Emerging Perspective

Singh, Salam Suresh; Thakur, Abhinay; Sandilya, Saumya
Department of Chemistry, Faculty of Technology and Science, Lovely Professional University, Phagwara, Punjab, INDIA

Kumar, Ashish+*
NCE, Aryabhatta Knowledge University, Department of Science and Technology, Patna, Bihar, INDIA

ABSTRACT: *Recently, the demands for biodegradable and renewable materials for several eco-sustain applications have increased tremendously. This rise in demand is connected to the growing environmental concerns over the extensive use of synthetic and non-biodegradable plastic packaging and the dumping of plastic waste in landfills. Biodegradable bioplastics are polymers that are mineralized into carbon dioxide, methane, water, inorganic compounds, or biomass by specific microorganisms by enzymatic action. As a result, they could be a viable and environmentally friendly alternative to petrochemical plastics. Bioplastic delivers precisely as per demand exhibiting several advantages: lower carbon footprint, energy efficiency, non-hazardous, stable, cost-efficient, and eco-friendly. Herein, a major focus is given to the discussion of bioplastic production from various sources, their type, and the role of additives to strengthen their chemical and physical properties. This review article's goal is to provide information about bioplastic synthesis concerning the recycling of bioplastics, thermoplastic biocomposites, and their blends with a special focus on the mechanical recycling of bio-based materials. Additionally, the utilization of these bioplastics in various industries such as the food packaging industry, and the automotive industry has been enlightened.*

KEYWORDS: *Biodegradable; Bioplastics; Synthesis; Polyhydroxyalkanoate; Additives*

INTRODUCTION

Plastics have been termed to be the most commonly used materials at the global level. Plastics are utilized in almost every manufacturing industrial sector, ranging from automobiles to medicine owing to its various versatile properties like strength, weather resistance, durability, dimensional stability, ductility, chemical and moisture resistivity, etc. [1]. The word "plastic" came from the word "Plastikos". On average, the production of plastic globally crosses 150 Million tonnes per year. Its broad range of applications is in packaging films, wrapping materials, shopping, and garbage bags, fluid containers, clothing, toys, household and industrial products, and building materials. Although, exponential growth in the human population has led to the accumulation of a considerable amount of non-biodegradable waste across our planet earth that causes adverse effects on the ecosystem and each individual linked to it [2].

Consequently, over the past 70 years, the rate of production of plastics has increased extensively from almost 0.5 million tons in 1950 to over 365 tons in 2016 globally. According to Plastics Europe, which is one of the leading European trade associations with centers all

***** *To whom correspondence should be addressed.*
+ *E-mail: drashishchemlpu@gmail.com*
1021-9986/2022/8/2704-2727 24/$/7.04

over the world stated that the tremendous rate of production of plastics touched 288 million tons in 2012 worldwide, which is still more remarkable if we compare it with 10-20 years ago, when their manufacturing was just overestimated 200 and 100 million tons, respectively. The tremendous growth of such high plastic usage simply attributes to their extraordinary physical properties, easy processing, and low-cost manufacturing. Such an increase in the huge production of plastic has led to many severe problems like an increase in carbon dioxide production resulting from the extraction, and processing of fossil fuel as plastic feedstock and combustion of waste plastic which increases carbon dioxide content in the atmosphere; thereby increasing health issues such as cancer, mental disorder, and reproductive and developmental disease problems due to the presence of many persistent organic pollutants in the environment like Furan, PCBs (polychlorinated biphenyl), short-chain chlorinated paraffin (SSCP), Chlorinated dioxin, polybromodiphenyl (PBDEs)[3]. When these plastics are disposed to nearby water bodies or grounds, it disturbs marine life and terrestrial communities, causing a significant problem in the surrounding environment.

Harmful effects of plastics

Plastic is versatile, lightweight, flexible, moisture-resistant, strong, and relatively inexpensive. Those are the attractive qualities that lead us worldwide to such a voracious appetite and over-consumption of plastic goods [4]. However, durable and prolonged to degrade, plastic materials used in the production of so many products, ultimately become waste. The tremendous attraction to plastic, coupled with an undeniable behavioral propensity of increasingly over-consuming, discarding, littering, and thus polluting, has become a combination of lethal nature. The disposal of plastics is one of the least recognized and most highly problematic areas of plastic's ecological impact. Ironically, one of plastic's most desirable traits: its durability and resistance to decomposition, is also the source of one of its most significant liabilities when it comes to the disposal of plastics. Natural organisms have a challenging time breaking down the synthetic chemical bonds in plastic, creating the tremendous problem of the material's persistence. A minimal amount of total plastic production (less than 10%) is effectively recycled; the remaining plastic is sent to landfills, where it is destined to remain entombed in limbo for hundreds of thousands of years, or to incinerators, where its toxic compounds are spewed throughout the atmosphere to be accumulated in biotic forms throughout the surrounding ecosystems.

Groundwater and soil pollution

Plastic is a material made to last forever, and due to the same chemical composition, plastic cannot biodegrade; it breaks down into smaller and smaller pieces. When buried in a landfill, plastic lies untreated for years. In the process, toxic chemicals from plastics drain out and sweep into groundwater, flowing downstream into lakes and rivers. The seeping of plastic also causes soil pollution and has now started resulting in the presence of microplastics in soil.

Pollution in oceans

The increased presence of plastic on the ocean surface has resulted in more severe problems. Since most of the plastic debris that reaches the ocean remains floating for years as it does not decompose quickly, it leads to the dropping of oxygen levels in the water, severely affecting the survival of marine species. Materials like plastic are non-degradable, which means they will not be absorbed and recycled. When oceanic creatures and even birds consume plastic inadvertently, they choke on it which causes a steady decline in their population. The harmful effects of plastic on aquatic life are devastating and accelerating. In addition to suffocation, ingestion, and other macro-particulate causes of death in larger birds, fish, and mammals, the plastic is ingested by smaller and smaller creatures (as it breaks down into smaller and smaller particles) and bioaccumulates in greater and greater concentrations up the food chain—with humans at the top. Even plankton, the tiniest creatures in our oceans, eats microplastics and absorbs their hazardous chemicals. The small, broken-down pieces of plastic are displacing the algae needed to sustain larger sea life that feeds on them.

To tackle and reduce these adverse effects of plastics on the environment, many scientists and researchers are looking for a novel, innovative eco- friendly solution to replace plastics and limit their usage worldwide. However, similar to conventional plastic many other types of plastics are synthesized from non-renewable fossil fuel which has biodegradable characteristics known as oxo-biodegradable plastic [5]. The main difference between oxo-biodegradable and conventional plastic is that the rate of degradability is fast in oxo-biodegradable plastic rather than conventional plastic. After being exposed to sunlight, heat, and other stress, oxo-biodegradable plastic quickly degrades into water, and carbon dioxide, and forms biomass. These fast biodegradable plastic (oxo-biodegradable) needs the same amount of fossil fuel during production and produce the same amount of greenhouse gases as Petro-plastic and conventional plastic [6].

Bioplastic refers to plastic made from plants or other biological materials using micro-organisms like Ralstonia eutropha and Pseudomonas oleovoran instead of fossil fuels [7]. It is also often called bio-based plastic and has a wide range of mechanical properties such as flexibility, durability, barrier, heat resistance, gloss, etc. Bioplastic can be directly obtained from many sources like vegetable wastes, plant material, plant waste residues, etc. Bioplastics can be used in different ways similar to conventional plastic and decomposed quicker than conventional plastic, producing less harmful substances, greenhouse gases in the environment, and minor problems in management[8]. The idea of biodegradable plastic production is an outstanding example of green chemistry in theory and can apply to many principles of green chemistry as a guideline for EPA (Environmental Protection Agency). Bioplastics are mainly designed for rapid degradation resulting in less production of harmful gases and are easily disposable which is the peak demand to sustain our mother earth and its ecosystem.

Classification and types of plastics

According to their characteristics, there are three types of classifications regarding plastics. According to their chemical structure, their polarity, and their applications. According to their chemical structure and temperature behavior, plastics can be divided into:

- Thermoplastics
- Thermosets
- Elastomers

Concerning polarity, the presence of atoms of a different nature causes electrons to move toward the most electronegative atom in covalent bonds, thus resulting in a dipole. Polymers containing these highly electronegative atoms, such as CI, O, N, F, etc., are polar compounds, which affect the properties of the material.

If the polarity is increased, the mechanical resistance, hardness, rigidity, heat resistance, water and moisture absorption and chemical resistance, and permeability to polar compounds such as water vapor and adhesivity and adherence to metals are also increased. At the same time, the increase in polarity reduces the thermal expansion, the electrical insulation capacity, the tendency to accumulate electrostatic charges, and the permeability to polar molecules (O_2, N_2). In this way, it is possible to distinguish between different families such as polyolefin, polyesters, acetals, halogenated polymers, and others.

Types of plastics

The third and last classification, according to their application, is applied to thermoplastic materials. There are four types of plastics:

1. Standard plastics or commodities: plastics manufactured and used in large quantities due to their price and good characteristics in many ways. Some examples are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), or the copolymer acrylonitrile butadiene styrene (ABS).

2. Engineering plastics: used when good structural, transparency, self-lubrication, and thermal properties are needed. Some examples are polyamide (PA), polyacetal (POM), polycarbonate (PC), polyethylene terephthalate (PET), polyphenylene ether (PPE), and polybutylene terephthalate (PBT).

3. Special plastics: They have a specific property to an extraordinary degree, such as polymethyl methacrylate (PMMA), which has high transparency and light stability, or polytetrafluoroethylene (Teflon), which has good resistance to temperature and chemical products.

4. High-performance plastics: mostly thermoplastic with high heat resistance. In other words, they have good mechanical resistance to high temperatures, particularly up to 150°C. Polyimide (PI), polysulfone (PSU), polyethersulfone (PES), polyarylsulfone (PAS), polyphenylene sulfide (PPS), and Liquid Crystal Polymers (LCP) are high-performance plastics.

Use of plastic in India and its management methods

"Plastic" is a synthetic polymer product with versatile properties and a wide range of applications such as low cost, strength, weather resistance, and durability plays a vital role in our daily life [10]. The consumption rate of plastic in India has increased from 400 Ton per year in 1992 to 5 metric Ton/year in 2005 and 8 Million Ton/years

Table 1: Classification of different types of plastic waste [9].

Types of Plastics	Plastic identification codes	Type of plastic polymers	Properties	Applications
Thermoplastic	01 PET	Polyethylene terephthalate	Transparent, strong, resistant to gas and moisture	Water and soft drink bottle, electronic application
	02 PE-HD	High-density polyethylene (HDPE)	Stiff, strength, tough, moisture resistance, permeability to gas	Water pipes, hula hoop rings, five-gallon buckets, milk, juice and water bottles, grocery bags, some shampoo/toiletry bottles
	03 PVC	Polyvinyl chloride (PVC)	Versatility, ease of blending, strength, toughness	Blister packaging for non-food items; cling films for non-food use. Non-packaging uses are electrical cable insulation rigid piping; vinyl records
	04 PE-LD	Low-density polyethylene (LDPE)	Ease of processing, strength, tough, Flexible, ease of sealing, a moisture barrier.	Frozen food bags; squeezable bottles, e.g. honey, mustard; cling films; flexible container lids
	05 PP	Polypropylene (PP)	Strength, toughness, resistance to heat, chemicals, grease and oil; versatile, barrier to moisture	Reusable microwaveable ware; kitchenware; yogurt containers; margarine tubs; disposable cups; soft drink bottle caps; plates
	06 PS	Polystyrene (PS)	Versatility, clarity, easily formed	Egg cartons; packing peanuts; disposable cups, plates, trays and cutlery; disposable take containers
		Nylon (polyamides)	Versatility, clarity, easily formed	Egg cartons; packing peanuts; disposable cups, plates, trays and cutlery; disposable take containers.
	PLA	Polylactic acid (polylactide)	Biodegradable thermoplastic derived from renewable resources, such as corn starch, sugarcane	3D printing with fused deposition modelling (FFF) techniques.
	PC	Polycarbonate	Easily mouldable	Applications, such as electronic components, construction materials, data storage devices, automotive and aircraft parts, and security glazing
	Acrylic	Poly methyl methacrylate (PMMA), Lucite, Perspex and Plexiglas	High strength and high-pressure resistant	Substitute for glass items as aquariums, motorcycle helmet visors, aircraft windows, viewing ports of submersibles, and lenses of exterior lights of automobiles
Thermoset plastic	07 O	Others	Poly methyl methacrylate (PMMA), Lucite, Perspex and Plexiglass	Food packaging wrappers (chips snacks etc.), electrical handles, knobs, adhesives and lamination for the work place, etc.
	Epoxy	Bisphenol an epoxy resin Novolac epoxy resin Aliphatic epoxy resin	High mechanical properties, temperature and chemical resistances	Applications including metal coatings, use in electronics / electrical components, high tension electrical insulators, fiber-reinforced plastic material and structural adhesive
	Silicone	Silicone	Low thermal conductivity, chemical reactivity, toxicity, Thermal stability	Electrical, electronics, household, Sealants for cooking apparatus
	Polyurathane (PU)	Polyurethane (PU)	High mechanical properties, temperature and chemical resistance,	Manufacture of nonflexible, high-resilience foam seating; rigid foam insulation panels; microcellular foam gaskets; durable elastomeric wheels and tires
	Polyester	Synthetic clothing	High-energy absorption material, insulating material in pillows, highly stain resistant (Polyester fabrics)	Films, tarpaulin, canoes, liquid crystal displays, holograms, filters, dielectric film for capacitors, film insulation for wire and insulating tapes.
	PI	Polyimide	Thermal stability, good chemical resistance, excellent mechanical properties, Thermoset polyimides exhibit very low creep and high tensile strength	Electronics industry for flexible cables, as an insulating film on magnet wire and for medical tubing,
	Melamine formaldehyde	Melamine resin	High tensile strength, high Specific Heat Capacity, high Electrical Resistivity	Kitchen utensils and plates (such as Melmac), ready-to-assemble furniture and kitchen cabinets, high-pressure laminates

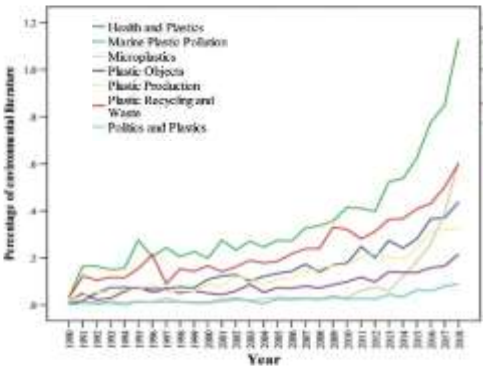

Fig. 1: Prevalence of literature—plastics debates (weighted) (Figure adapted from source [12]).

in 2008; estimated to rise to 24 million Tons in 2020. The commercial scenario of plastic usage in a developed country and penetrating it into a developing country can cause a high obsolescence rate of plastic waste as it is the fastest-growing waste stream [11]. The USA ranks highest for the annual consumption of plastic globally (38.9 MT), followed by China (38.8 MT), and followed by India as contributing third-highest ranking in consumption of plastic with annual consumption of 12.5 MT in 2009. Among the several types of plastic polymers, low-density polyethylene (LDPE) followed by high-density polyethylene (HDPE) and PP are among the most consumed plastic. Fig. 1 shows several works of literature conducted concerning plastics debates (weighted) [12].

The annual per capita consumption of plastic in India in 1990-1991 was 0.8kg but after a decade, there was an exponential rise in the consumption of plastic at the rate of 3.5 kg in 2000. However, according to global consumption which is 18kg, India is far below but according to some projected studies, there may be 10.9kg of plastic consumption in 2021. In addition, all of the global 17 sustainable development goals, as shown in Fig. 2, will also not be achieved [13].

According to Central Pollution Control Board (CPCB), the amount of plastic waste in municipal solid waste in India is 8%. The capital of India, Delhi contributes the maximum quantity of plastic waste, closely followed by Kolkata and Ahmedabad. As per the 2014 report of CPCB, the collection efficiency of plastic in India is 80.28%. Among them, only 28.4% were treated and the remaining quantities were disposed of in a landfill or open dumps. In India, plastic waste treatment is a major problematic issue because here people are not aware of the harmful impacts of plastics on their health and surroundings. There is also a lack of knowledge about the minimization, reused, and recycling of plastics. In India, landfill contribute the highest disposal of plastic (60-70%), followed by incineration (20-25%) and recycling (10%)[11].

Although to minimize the use of such hazardous plastic in India and to limit the toxic effects of such, several waste management acts have been practiced in the country such as Plastic Waste Management (PWM Rules), 2016. The Government of India notified Plastic Waste Management (PWM) Rules, 2016 on 18th March 2016, superseding Plastic Waste (Management & Handling) Rules, 2011. These rules were further amended and named Plastic Waste Management (Amendment) Rules, 2018.

Salient features of Plastic Waste Management (PWM Rules), 2016

- These rules shall apply to every Waste Generator, Local Body, Gram Panchayat, Manufacturer, Importer, Producer, and Brand Owner.
- Carry bags made of virgin or recycled plastic, shall not be less than fifty microns in thickness. The provision of thickness shall not be applicable to carry bags made up of Compostable plastic, complying with IS/ISO: 17088.
- Waste Generators including institutional generators and event organizers shall not litter the plastic waste, shall segregate waste and handover to an authorized agency, and shall pay the user fee as prescribed by ULB and spot a fine in case of violation.
- Local Bodies shall encourage the use of plastic waste for road construction or energy recovery or waste to oil or co-processing in cement kilns etc. It shall be responsible for the development and setting up of infrastructure for segregation, collection, storage, transportation, processing, and disposal of the plastic waste either on its own or by engaging agencies or producers
- Gram Panchayat either on its own or by engaging an agency shall set up, operationalize and coordinate for waste management in the rural area under their control and for performing the associated functions, namely, ensuring segregation, collection, storage, transportation, plastic waste, and channelization of the recyclable plastic waste fraction to recyclers having valid registration; ensuring that no damage is caused to the environment

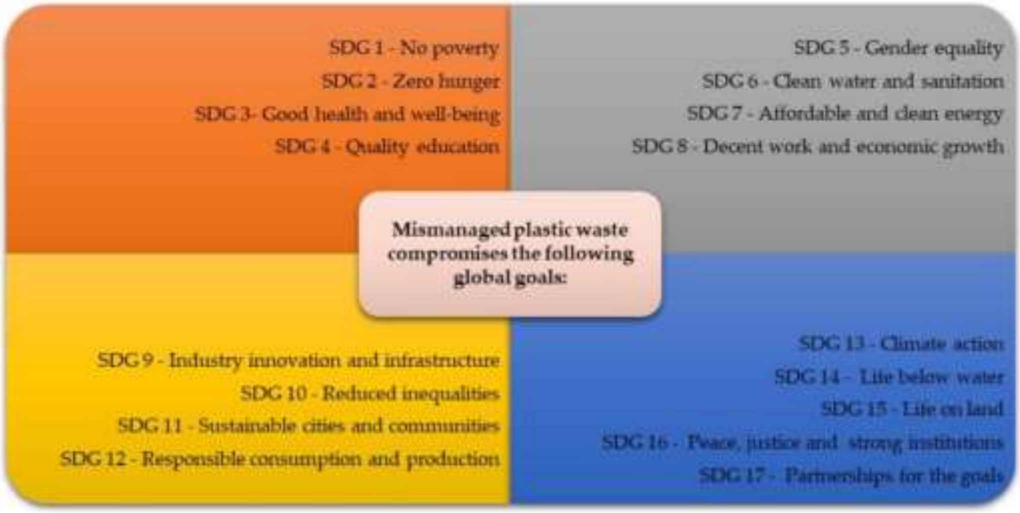

Fig. 2: Effect of mismanaged plastic waste on the global goals (Figure adapted from source[13])

during this process; creating awareness among all stakeholders about their responsibilities; and ensuring that open burning of plastic waste does not take place Producers, Importers, and Brand Owners need to work out modalities for waste collection systems for collecting back the plastic waste within six months in consultation with local authority/State Urban Development Department and implement with two years thereafter.

- State Pollution Control Board (SPCB)/ Pollution Control Committee (PCC) shall be the authority for enforcement of the provisions of PWM Rules, 2016, relating to registration, manufacture of plastic products and multi-layered packaging, processing, and disposal of plastic wastes.
- Concerned Secretary-in-charge of Urban Development of the State or a Union Territory and concerned Gram Panchayat in the rural area of the State or a Union Territory shall be the authority for enforcement of the provisions of PWM Rules, Rules relating to waste management by the waste generator, use of plastic carry bags, plastic sheets or like, covers made of plastic sheets and multi-layered packaging.

BIOPLASTICS

The term “Bioplastic” is not new; a British chemist coined the term Bioplastic in the 1850s after synthesizing plastics from cellulose, extracted from wood pulp. Bioplastic is a type of plastic that is extracted from various plant sources or biopolymers. After the beginning of the 20th century, Henry ford experimented and tried to substitute fossil fuels for powering numerous automobiles with soya plastics. Later, biodegradable plastics started hopeful interest, particularly in the midst oil crisis of 1970[14]. Like plastic, Bioplastics can also be synthesized from fossil fuels. Bioplastic synthesize from raw vegetable materials, animals, bacteria [15], food waste [16] and microbes also have some similar mechanical properties to conventional plastic. Although some of the bioplastics are not so quickly biodegradable in a normal environment but do not have a slow rate as conventional plastic does.

The term “Biodegradable” is defined as a characteristic of materials that can quickly degrade by microbes to a simple less toxic final product like carbon dioxide and water, and don’t possess any harmful effects on the environment. Biodegradable plastic is simply defined as a substance whose physical and chemical properties change on decomposition when surrounded by microorganisms/ microbes attributing aerobic processes (into carbon dioxide in the presence of oxygen) and anaerobic processes (into methane in the absence of oxygen) with a definite period. The decomposition of bioplastics with time depends on external environmental conditions like temperature, humidity, and place of decomposition. A compostable group of plastic gets easily degraded by microbes and converts into humus with less amount of toxicant as residue. Compostable plastic possesses definite degradable capabilities and various international standards like EN 13432:2000, ISO 17088:2012, and ASTM D6400-12.

According to European standard EN 13432:2000, within six months, 90% of plastic should be converted into carbon dioxide and all particulate matter should be converted into residue with less amount of dimension below 2mm.

Bioplastics are synthesized from natural sources like microorganisms, plants, animals, agro waste, etc. Also, some monomers like sugar, disaccharides, and fatty acids can be used as raw materials for bioplastic production. Bioplastics synthesized from microorganisms, plants, and animals or artificially manufactured from biotic things utilize resources like starch, cellulose, and lactic acid. To preserve and solve the non-renewable fossil fuel energy issue and environmental-related problems, there is a huge need to synthesize many bioplastics which will help increase the reduction of carbon footprint materials and fewer issues in waste management.

The idea of biodegradable plastic is a golden part of green chemistry and attains a broad scope in our modern society. Bioplastics have many environmental advantages like less energy consumption in production, fewer environmental problems, fewer health issues, less carbon dioxide emission, easily and rapidly degradable and safe for consumption. The production of bioplastics consumes less than 65 percent of energy as compared to petroleum-based plastic. These are completely non-toxic and can be broken down into non-toxicant substances like water and carbon dioxide mainly. Bioplastic emits fewer greenhouse gases to the atmosphere as compared to petroleum base plastic. Theoretically, bioplastics seem to be a perfect candidate in replacement of toxic and non-biodegradable conventional plastic but practically, bioplastics are still in their infancy and there is still a large room for improvement to be made in this field. Bioplastics are driving the evolution of plastics. There are two major advantages of biobased plastic products compared to their conventional versions: they save fossil resources by using biomass which regenerates (annually) and provides the unique potential of carbon neutrality. Furthermore, biodegradability is an add-on property of certain types of bioplastics. It offers additional means of recovery at the end of a product's life.

Sustainability

During the manufacturing of plastics, chemical additives are used to enhance the properties of plastic. But more than improving the properties of plastic, this chemical additive imposes more negative impacts on the environment than plastics[17]. Each year there is huge dumping of several million tons of plastic into the ocean, which makes a plastic soup on the ocean surface[18]. Also, many particulate sizes of plastic are scattered in the different ecosystems through wind, water, birds, and other agents. This micro particle of plastics clogs the pipelines and disturbs the sewage and drainage system[19]. Nowadays, many health-related issues due to plastic are mainly coming from their monomeric unit (e.g., Bisphenol A) or additives (e.g., plasticizer) or sometimes from the combination of the two (e.g., antimicrobial polycarbonate) which results in illness, fatality or abnormality in various living organisms after consuming the microparticle which seems to be a food material or plastic derived packing used in food items [20]. Fig. 3 discusses the basic concept with steps and criteria for sustainable plastic. To prevent or decrease its extent of negative impact on the environment and human health, the use of eco-friendly bags or bioplastics is of great help [21].

The concept of sustainability has some glimpse against the toxic effects of plastic and fulfills some basic encouraging concepts which are safe for the environment. Sustainable products of plastic decrease the extent of negative effects on the environment and deliver benefits to society by decreasing the health-related issues on humans and safely securing the entire product [22-25]. According to the definition of sustainable plastic, sustainable plastic is arranged within a continuous material arrangement system to exclude making waste, toxic, and pollution. Making sustainable plastic is not a hide and seeks play as it involves the selection of appropriate material to produce a high-quality product and modification in the system where the product is being utilized. For getting a sustainable remark, the product should be satisfied with the requirement of a healthy atmosphere and holistic outputs [26].

Type of bioplastic

The bioplastics are synthesized from different materials having unique properties, and their application is different according to their manufacturing process. Bioplastics are usually categorized into three main groups:

Bio-based plastics– These include bioplastics made out of bio polyesters. Polyethylene (PE), polyethylene terephthalate (PET) and certain polyamides (PA), and polyurethanes (PUR) are included in this category.

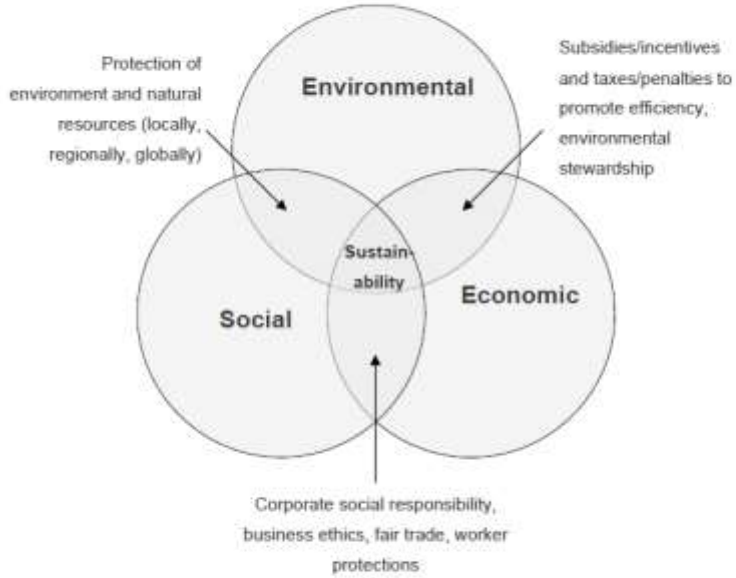

Fig.3: Sustainability as the intersection of its three key parts, and examples of features at the intersection of any two parts (Figure adapted from source[21])

Bio-based and biodegradable plastics–These include versions like polylactic acid (PLA), polyhydroxyalkanaoates (PHA), polybutylene succinate (PBS) [27].

Fossil-based but biodegradable plastics- These include PCL, PBAT, etc.

However, the following are the most common bioplastics being used in the present day:

Starch-based bioplastics

The bioplastics synthesized from maize starch were the first Bioplastic, which substituted plastic and was marketed under the name "Evercorn TM and nature works"[28]. Previously plastics were produced by mixing petrochemical plastic polymer in the presence of starch polymeric compounds which were biodegradable and now these are synthesized from starch fermentation extracted directly from potato corn, wheat, tapioca, etc. with the help of microorganisms. At the time of bioplastic disposal, microbes rapidly degrade the starch molecules present in bioplastics. These have fewer physical and chemical properties than petrochemical plastic[29]. The starch-based bioplastics have some stability effects when they are exposed to moisture. For example, Polylactic acid (PLA), polyhydroxyalkanoates (PHA)[30,31], a new generation of bioplastics that are synthesized from starch and carbohydrate as raw material for bio-based, polyolefins polyethylene (PE) and polyvinyl chloride (PVC), and the partially bio-based polyethylene terephthalate (PET).

Cellulose based bioplastics

Cellulose is a long-chain polymer of glucose in which long-chain units of glucose are linked by β-1,4- glucosidic bond. Cellulose is present in the cell wall of plants, green algae, and some fungi. The cellulosic polymers are obtained after the removal or alteration of the chemical composition obtained from natural cellulose. Cotton fibers and wood pulp are the two primary raw materials to obtain cellulosic plastic and organic cellulose. Ester and regenerated cellulose are the two main types of cellulose for the synthesis of bioplastics. Esterification of cellulose with organic acid is the process for the formation of organic cellulose and approximately 20% of the overall total chemical category pulp is used for the fabrication of organic cellulose esters. Several organic cellulose esters which play an important role in industries are Cellulose Acetate (CA), Cellulose Acetate Propionate (CAP), and Cellulose Acetate Butyrate (CAB). These are used for various industrial purposes such as manufacturing wrapping film, making filters of cigarettes, textile fibers, pharmaceuticals, etc. In the production of regenerated cellulose, firstly, cellulose is dissolved in chemicals and then a new form of fibers or film is formed which is further modified. At present, more than 60% of the overall total chemical category pulp is used for the manufacture of cellulose regenerates. Various examples of cellulose-based bioplastics are viscose, viscose silk, lyocell, and rayon [16].

Polylactic Acid (PLA) based bioplastics

Polylactic acid (PLA) bioplastic is one of the plastics commonly used in the market today. PLA is synthesized from the fermentation of starch to produce lactic acid. The main sources of starch are maize, cassava, potato, sugarcane, and sugar beet. PLA plastic is more advantageous than starch-based plastic. For the synthesis of PLA, plant starch is changed into lactic acid to get monomer through fermentation with the help of microorganisms and then chemically treated the lactic acid to form a long chain of lactic acid. This PLA plastic is somewhat similar to fossil fuel-based plastics but it is a decomposable plastic. Some benefit of PLA plastics includes high rigidity, stability, transparency, thermoplastic and better presentation in the active equipment of fossil fuel-based plastic manufacturing industry which emits 70% fewer greenhouse gases at the time of degradation and landfill; consume less energy at the time of production than those of petrol chemical plastic. Due to their versatile properties, PLA plastics are used widely in food packaging, the manufacturing of molded parts, drinks containers, cups, bottles, and other everyday items. The function of PLA plastics is also growing and has enormous scope in various sectors like medical applicants, textile, cosmetic industries, and household usage. Moreover, the automobile industries manufacture dashboards, door tread plates, etc. from PLA-based plastics.

Polyhydroxyalkanoates (PHA) based bioplastics

Polyhydroxyalkanoates (PHA) is a type of bioplastic synthesized through microbial fermentation by using starch obtained from plants as raw material and biodegrades within one year. PHA possesses similar physical and chemical properties as polyesters, polyethylene, and polypropylene. Some company manufactures PHA bioplastics on a large scale using polyhydroxy butyric acid (PHB) and Polyhydroxybutyrate, polyhydroxy valerate (PHV), poly-3- hydroxybutyrate-valerate (PHBV) as their raw materials. A few examples of Polyhydroxyalkanoates are Biopol and Bionelle. Prokaryotes and archaea are two main microbes having a good capability to generate PHA intracellular. Some bacteria like Alcaligenes spp., Pseudomonas spp., and many filamentous genera viz., Nocardia spp. can yield these PHAs with insufficient nutrients. Biodegradation of PHA under anaerobic conditions emit carbon dioxide and water; as of its non- toxic and natural polymer characteristics, it can be used in several applications like packaging food, medical implant, and agriculture.

Drop-in bioplastics

Drop-in is a type of non-biodegradable bioplastics synthesized by using completely or partially bio-based materials. However, this bioplastic is manufactured by using corn, sugarcane, and sugar beet as raw materials. Drop-in bioplastic is a new method that embeds the conventional petrochemical with raw materials like corn, sugarcane, and sugar beets-based bioplastics and the only difference from conventional petrochemical plastic is that it is partially biodegradable. Some examples of drop-in bioplastics are bio-polyethylene (PE), bio-polypropylene (PP), and bio-polyethylene terephthalate (PET). Bioethanol is a type of renewable resource that is used as raw material for the manufacturing of different types of conventional plastic like polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC). A bio-based product succinic acid is a good source showing numerous applications in different scopes like sports, automotive, packaging, fiber applications, agriculture, etc. These bioplastics help reduce carbon footprint and production cost due to their renewable biomass composition which allows their recycling usage[16].

Fossil Fuel-based Bioplastics

This type of bioplastics with biodegradable characteristics is manufactured from petrochemical raw materials. A conventional petrochemical product like poly butyrate adipate terephthalate (PBAT) is also a type of raw material used to manufacture bioplastics. A new group of polymers is synthesized from the petrochemical product which has biodegradable characteristics commonly known as poly butyrate which embed with starch and other bioplastic materials to attain specific applications due to its attributes such as decomposability and inflexibility. The manufacturing rates of new bio-based or partly bio-based versions of PBAT have increased in recent years. The main advantages of this type of bioplastics have high elasticity, fracture resilience, and flexibility. These are used in making bags, wraps, dust-bin bags, disposable packaging, and other packaging materials[16]. Biodegradable polymers may be classified into different types according to their synthesis processes and sources, as shown in Fig. 4 [32].

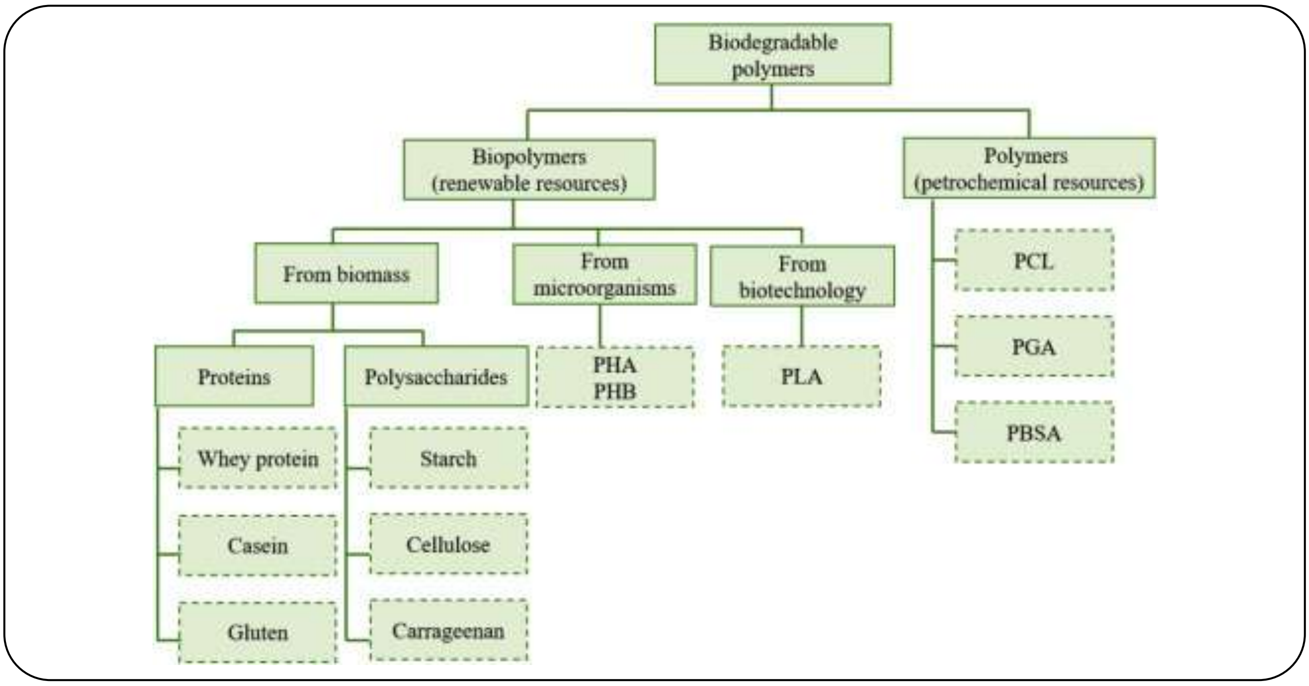

Fig. 4: Classification of biodegradable polymer (Figure adapted from source [32]).

METHODS OF BIOPLASTIC PRODUCTION

From Plants

The production of bioplastic from microorganisms is complex and associated with many limitations. One of the major drawbacks is the high cost and challenging process; even more cost than petro-based plastic. Potentially and profitably, plants offer a chief and cheap source as a raw material for the synthesis of these huge commodity products known as "Bioplastic" at low cost. Bioplastic synthesized from the plant is more eco-friendly than microorganisms and petro-based bioplastic as plant-synthesized bioplastic depends on the soil, water, and carbon dioxide.

From microorganisms

Bioplastic synthesis from microorganisms under different environmental conditions is increasing vigorously at a global level. The water-insoluble compound such as polyhydroxyalkanoic acid in the prokaryotic cell which behaves as a storage polymer is considered raw material for bioplastic. The physical properties, molecular structure, and monomer composition of different bioplastics depend on the origin of the microorganism. Most of the bioplastic extracted from microorganisms is biodegradable and biocompatible. Fig. 5 illustrates a diagrammatic representation of the manufacturing process of PHA bioplastic [33].

From other sources

Other than plants and microorganisms, *Quil et al.* used the poultry feather as raw material for synthesizing bioplastic. Under the different plasticizers, keratin was extracted from the feather and then extruded in a twin-screw extruder with sodium sulfate treatment as a reducing agent. Tsang et.al. used a different source of food waste as a raw material for bioplastic production. Table 2 discusses bioplastics production from various raw materials along with their methodology. Additionally, such a type of innovation has reduced environmental landfill problems as well as petro-based plastic production.

ROLE OF ADDITIVE IN BIOPLASTICS

The several applications of plastic material are successful in various sectors like the automotive industry, electronic sector, the packaging sector, the manufacturing industries of consumer and goods, etc. But the virgin polymeric material often exhibits poor properties and acts as the main result of commercial failure. According to EC, an additive is defined as a substance that is incorporated into the plastic to achieve a technical effect in the finished product and is intended to be an essential part of the finished article. Different additives have different functions like antioxidants, light stabilizers, UV absorbers,

Table 2: Bioplastics production from different raw materials and their methodology.

Source	Raw material	Methodology's	Reference's
Plants	Banana peel	FTIR, DSC, weight loss, load test	[34]
	Perennial grass (*Miscanthus fibre)*	SEM, ASTM, DSC, FTIR	[35]
	Gum arabic	ATR-FTIR, TGA, XRD, SEM, AFM	[36]
	Potato	XRD, NMR, FTIR	[37]
	Yellow Pumpkin	Weight loss, tensile strength	[38]
	Rice straw	SEM, EDXS,XRD, FTIR	[39]
	Algae (Spirulina platensis)	UV spectrophotometer,	[40]
	Oil palm	FTIR, Tensile streght,ASTM	[41]
	Algal biomass	DSC, TGA/STDA851e, DMA	[42]
	Cassava peel (*Manihot utilisima)*	Tensile strength, weight loss, FTIR, SEM	[43]
	Edible vegetable waste	TGA/DSC, SEM , AFM, ASTM, XRD	[7]
	Ground nut	FEG-SEM, Weight loss, FTIR, ASTM	[44]
	Mango seed	FTIR, weight loss, tensile strength, SEM,	[45]
	Mulberry	SEM, FTIR, tensile strength,	[46]
	Neem	ASTM, Swelling and solubility test	[47]
	Giant red grass	NMR, FTIR, TGA, DSC	[48]
	Sagrassum siliquosum	FTIR, weight loss, ASTM	[49]
	Micro algae	Gas chromatography, electron microscope, Fluorescence	[50]
Microorganisms	*Bacillus meggaterium, Pseudomonas oleovorans*	AFM, Raman spectroscopy	[51]
	Chelatococcus thermostellatus sp	SEM, TEM, PCR analysis, fatty acid analysis	[52]
Others	Feather quill	FTIR, DSC, TGA, DMA	[53]
	Newspaper waste	TGA, FTIR, DMA	[54]
	Agro waste	SEM, FTIR, ASTM, TFA	[55]
	Fish scale	SEM, FTIR, TGA, DMA	[56]
	Food waste	DMA, FTIR, TGA	[33]

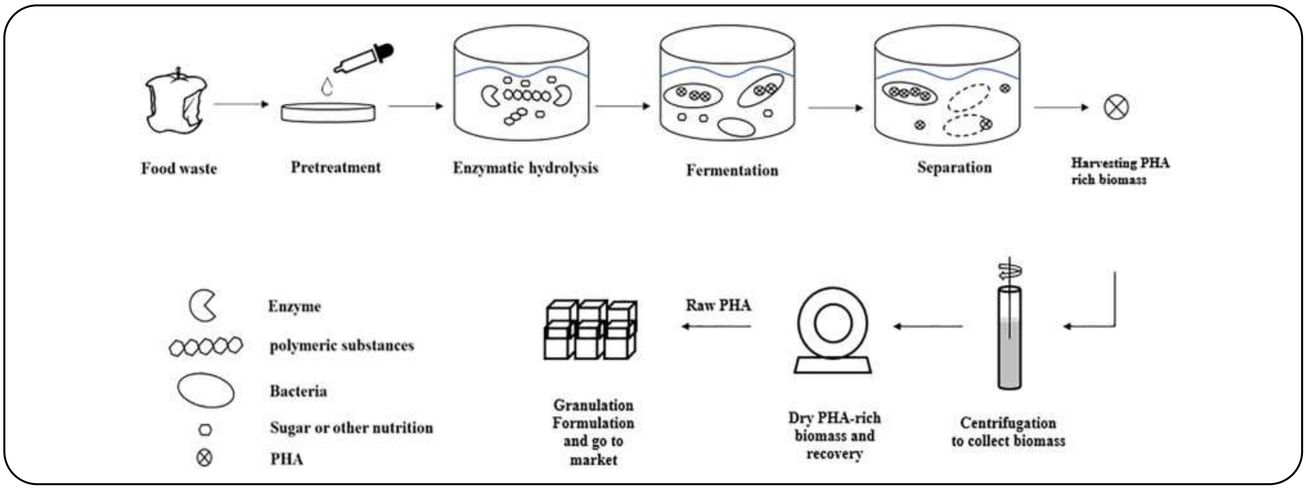

Fig.5: Manufacture process of PHA bioplastic (Figure adapted from source[33]).

flame retardants, heat stabilizers, impact modifiers, plasticizers, compatibilizers, coupling agents, colorants, pigments, whiteners, etc. The process of activation in a polymer can be performed in a different stage of polymer processing: during the production of polymer inside the reactor; at the finishing stage of polymer processing by blending or mixing. Although, sometimes activation can also be performed by directly applying it to the surface of the finishing product [57]. Biodegradable additives can convert the plastic degradation process to one of biodegradation. Instead of being degraded simply by environmental factors, such as sunlight (photo-oxidation) or heat (thermal degradation), biodegradable additives allow polymers to be degraded by microorganisms and bacteria through direct or indirect attack [58].

Type of additives

Plasticiser

Plasticiser is one of the most important additives which were used in 19 century. Typically, plasticizers have linear or cyclic carbon chains with an average molecular weight of 300 to 600. These are high boiling point liquids with a low molecular size that helps them to penetrate the intermolecular spaces in the polymer chains leading to lower secondary forces between the chains. This changes the three-dimensional network of the polymer chains which eventually gives higher mobility by increasing the free volume. Therefore, the chemical structure of the plasticizer along with the molecular weight, functional groups, and chemical composition plays a vital part in deciding the degree of plasticity. According to the Council of the International Union of Pure and Apply Chemistry (IUPAC), Plasticiser is defined as a substance or material incorporated in a material to increase its flexibility, workability, or sensibility [59]. Based on the nature of the plasticizers; they are classified into two categories: hydrophilic and hydrophobic plasticizers. Hydrophilic plasticizers when added to polymer dispersions dissolve in an aqueous medium such as glycerol, polyethylene glycol (PEG), and ethylene glycol. They can lead to enhanced water diffusion in the polymer if added to higher concentrations. Hydrophobic plasticizers such as phenyl ethers, citrate esters, phenyl esters, and stearyl esters, on the other hand, can lead to a decrease in water uptake as they close the micro-voids in the films.

Antioxidants

The antioxidant additive is used mainly to prevent or lower the rate of the oxidation cycle in polymers by scavenging the free radicals. During the compounding or processing of plastics, oxidation occurs and creates issues like loss of strength, breakdown, or discoloration. But sometimes oxidation may occur at the final stage of the product and causes discoloration, scratching, flexibility, stiffness or gloss, and loss of strength. The cause of degradation is always by oxygen or UV radiation attack. The process of oxidation can be done by oxygen or ozone under ambient or elevated temperatures. At higher temperatures, the oxidation process is effectively prohibited by anti-oxidants but there is a formation of color chromosphere which leads to other deleterious changes in coating properties. Most antioxidants are used in hydrocarbon polymers including polyethylene, polypropylene, polystyrene, etc. [60].

Flame retardants

In the presence of heat and oxygen, all carbon-based materials from wood to plastics can be combusted. Combustion is the basic step for the production of energy in all living cells. The combustion of fossil fuels is a cheap source of energy for humanity. In combustion, energy is absorbed until the C-C, C-O, C-N bond in the backbone breaks and releases many toxic gases into the atmosphere like oxygen, sulfur, fluorine, chlorine, etc. The combustion nature of the organic polymers changes when flame retardants are introduced into the organic polymer. Flame retardants change the chemistry of the combustion process. Further, flame retardants can be divided into three based on their technology a) Halogen-based flame retardants, b) Phosphorus-based flame retardants, and c) Metal hydrate flame retardants[57]. In metal hydrate flame retardants, many hydrate substances like Magnesium hydroxide can be used as effective flame retardants in many ways. Metal hydrate flame retardant has a substantial amount of water (31% for magnesium hydroxide) and this water comes out at a high temperature and reduces the viability of oxygen after the act as a blanket. Metal hydrate flame retardant also helps in reducing heat and smoke by absorbing them[61]. Halogen-based flame retardant also plays a major role but due to rising environmental issues and concerns, there has been growing interest in halogenate-based flame retardants. The performance of halogen flame retardant is I > Br > Cl > F [62,63].

Heat stabilizers

During the processing of plastics, many plastics degrade due to heat. So, a heat stabilizer is used to prevent the degradation of plastic by inhibiting thermal oxidation. A mixture of heat stabilizers and chlorinated polymer is often used for the abstraction of hydrogen chloride and prevents acid from further catalytic action. Heat stabilizer is mainly applied in PVC plastics due to the high sensitivity of PVC to heat. One of the major applications of the heat stabilizer is the recycling process by preventing the plastic materials from getting degraded and re-stabilized post-used plastic, which acts as a double role. During bake, heat stabilizers are applied in Plastisols and organosol to prevent degradation. Barium and a calcium salt of NP are used for PVC heat stabilizers[60]. Depending upon the type of oxidation, various heat stabilizers like metallic salts (stabilize PVC), organometallic compounds, non-metallic organic stabilizers, organophosphates, and epoxies are commercially available.

Slip agents

Slip agents additive is used mainly to modify the surface properties of a film, smoothing the surface of a film that helps reduce the fraction between two films. It helps in making a smooth glide between the two surfaces without creating any mechanical damage, improving the flow characteristics during processing and thereby increasing the physical properties. Slip additives are available in two states i.e. solid and liquid. Among the two states, solid-state is conventionally used in dry, dispersed, or emulsion forms. Fatty acid ester is used as a slip additive for the production and modulation of polyethylene terephthalate [64]. Slip additives can be used in polymer film structures and plastic packaging to improve polymer processing and in-use properties and are a practical requirement for both the manufacturer and end-product consumer.

Dyes and pigments

Among the plastic additives, dyes, and colorants are widely used in different sectors like textiles, leather goods, and food and personal care products. For the coloring of a product, other states of coloring additives like dry color, liquid color, the color concentrate can be used. Coloring additives are also used to change the physical properties such as repel light and sometimes it is used for aesthetical purposes. Among the dye, an organic dye is stronger and more widely used than inorganic dyes [60].

Filler additives

The substance is added to a polymer formulation to increase its properties and lower the cost of raw material is known as filler. Filler additive exists in different forms like solid, liquid, and gases. Filler additives can be classified into extender and functional filler[65]. One of the main contributions of filler additives is reducing the cost of material by replacing the expensive polymer. This material is quite economical and can improve mechanical properties like reducing thermal expansion, mold shrinkage, etc. Based on the different types of filler, other polymer properties may be affected by increasing the melting velocity if the polymer is mixed with fibrous material. Several types of fillers used in plastics are alumina trihydrate, kaolin clay, calcium carbonate, talc, etc.

Bio-based additive

Due to several versatile physical properties and cost-effectiveness, plastic polymers are used in different sectors for more than fifty years. It's quite difficult to imagine our modern life without synthetic polymers. But this valuable plastic polymer has not revolutionized our daily life, and also adversely affected our environment and nature. Therefore, researchers developed many bio-based plastics to replace fossil fuel-based plastic but the use of the synthetic additive in bio-based plastic also creates environmental problems. The manufacturing of additives also negatively impacts the environment as the raw material used for additive production is neither green nor sustainable. So, many research groups have developed bio-based additive which is sustainable and non-toxic to the environment [66]. But bio-based additive is not convenient as fossil fuel-based additive as they can be applied only to a specific range of plastics and still, there is a lack of study, knowledge, and information about bio-based additives. Table 3 shows the type of additive used in plastics.

BIOPLASTIC DEGRADATION

To solve the issues that occurred due to plastics pollution and make a sustainable environment, the biodegradable polymer has been introduced in past decades. Due to its eco-friendly and cost-effective nature, the manufacturing of bioplastic has increased tremendously

Table 3: Type of additive used in plastics.

Type of additive	Amount of additive	Material used	Remarks
Functional additives			
Plasticizer	10-70	Short and medium chain chlorinated paraffins (SCCPMCCP); Diisoheptylphthalat (DIHP); DHNUP; Benzyl butyl phthalate (BBP); Bis (2-ethylhexyl)phthalate (DEHP): Bis(2-methoxyethyl) phthalate (DMEP): Dibutyl phthalate (DBP); Diisobutyl phthalate (DiBP); Tris(2-chloroethyl)phosphate (TCEP);	Around 80 % is used in PVC and the remaining 20 % in cellulose plastic
Flame retardants	12 – 18 (for brominated)	Short and medium-chain chlorinated paraffin (SCCPMCCP): Boric acid; Brominated flame retardants; Tris(2-chloroethyl)phosphate (TCEP)	Three groups: organic non-reactive, reactive; inorganics.
Stabilizers, Antioxidants, and UV stabilizers Heat stabilizers	0.05- 3 0.5 -3	Bisphenol A (BPA); Cadmium compounds; Lead compounds; Nonylphenol compounds; Octylphenol; 1,3,5-Tris(oxiran-2-ylmethyl)- 1,3,5-triazinane-2,4,6-trione (TGIC)/1,3,5-tris[(2S and 2R)- 2,3-epoxypropyl]-1,3,5-triazine-2,4,6-(1H,3H,5H)- trione (β-TGIC) Used in PVC. Based on lead, tin, barium, cadmium, and zinc compounds. Lead is most efficient and used in lower amounts.	The amount depends on the chemical structure of the additive and of the plastic polymer. Phenolic antioxidants are used in low amounts and phosphites are in high. Lowest amounts in polyolefins (LLDPE, HDPE), higher in HIPS and ABS Cadmium compounds; Lead compounds; Nonylphenol (barium and calcium salts);
Slip agents	0.1 – 3		Amounts depend on the chemical structure of the slip agent and plastic polymer type
Lubricants (internal and external)	0.1 - 3		
Antistatics	0.1-1		Most types are hydrophilic and can migrate to water
Curing agents	0.1-2	4,4'- Diaminodiphenylmethane (MDA); 2,2'-dichloro-4,4'-methylenedianiline (MOCA); Formaldehyde - reaction products with aniline; Hydrazine; 1,3,5-Tris(oxiran-2-ylmethyl)- 1,3,5-triazinane-2,4,6-trione (TGIC)/1,3,5-tris[(2S and 2R)- 2,3-epoxypropyl]-1,3,5- triazine-2,4,6-(1H,3H,5H)-trione (β-TGIC)	Peroxides and other crosslinkers, catalysts, accelerators
Blowing agents	Depends on the density of the foam and the potential gas production of the agen		Azodicarbonamide, benzene di-sulphonyl hydrazide (BSH), pentane, CO_2
Biocides	0.001-1	Arsenic compounds; Organic tin compounds; Triclosan;	Soft PVC and foamed, polyurethanes are the major consumers of biocides. They are of different chemical structures and include chlorinated nitrogen sulphur heterocycles and compounds based on tin, mercury, arsenic, copper, and antimony, e.g. tributyltin and 10,10´-oxybisphenoarsine

Table 3: Type of additive used in plastics. (Continuation)

Type of additive	Amount of additive	Material used	Remarks
Colorants			
Soluble (e.g. azocolorants)	0.25-5		Migrates easily. Used in highly transparent plastics. They are expensive and have limited light- and heat resistance. They are used in PS, PMMA, and cellulose plastics to give a bright transparent color
Organic pigments	0.001-2.5	Cobalt(II) diacetate	Insoluble low migration tendency
Inorganic pigment	0.01-10	Cadmium compounds; Chromium compounds; Lead compounds	E.g. zinc sulfide, zinc oxide, iron oxide, cadmium-manganese-based, chromium-based, ultramarine, and titanium dioxide
Special effect	Varies with the effect and substance in question		Aluminum and copper powder, lead carbonate or bismuth oxychloride, and substances with fluorescence might migrate, the former no
Fillers	Up to 50		Calcium carbonate, talc, clay, zinc oxide, glimmer, metal powder, wood powder, asbestos, barium sulfate, glass microspheres, silicious earth
Reinforcements	Glass (15 - 30%)		Glass fibers, carbon fibers, and aramid fibers. 15-30% is for glass only due to the high density of glass.

since 2016 and as of now, it is estimated to produce 1.13 million tons of bioplastic per year in Europe [67]. Biodegradation is the degradation process involving microorganisms, is widely accepted as selective, and depends on several factors including the physical and chemical properties of biopolymers. The biodegradation process is defined as polymer degradation by biological microorganisms into CO_2, H_2O, biomass, and methane by composting, soil biodegradation, marine biodegradation, or other biodegradation processes. It is also termed biotic degradation and can be enhanced or started after some initial abiotic degradation processes occur such as mechanical, oxidative, or hydrolytic degradation which can increase the surface area of the organism–polymer interface. Down below, Fig. 6 shows the mechanism of the bioplastic degradation process by microorganisms in the marine environment [68].

Aerobic decomposition of bioplastics

The biodegradation of bioplastic can be done in different environmental conditions. Soil and composting are the two common types of bioplastic biodegradation under aerobic environmental conditions. The aerobic environmental degradation of bioplastic is mainly performed with different enzymatic actions of high diversity microbial population and digests different organic waste with the warm and moist environment under control conditions. The aerobic decomposition of bioplastic is considered an eco-friendly phenomenon. Humic compounds and CO_2 are the main by-products of the aerobic decomposition of bioplastic, however, CO_2 does not contribute to greenhouse gases as its part of the elemental cycle [69]. Table 4 discusses the aerobic decomposition of bioplastic in various environmental conditions and times [69].

Anaerobic decomposition of bioplastics

In the anaerobic decomposition of bioplastics, trash bioplastics are mainly obtained from food packaging, kitchen food waste, etc. In anaerobic decomposition, anaerobes secrete an external enzyme and digest the bioplastic through hydrolysis and convert long-chain polymers into oligomers and monomers. These small oligomers and monomer diffuses through the cell wall and digests inside the cell wall by internal enzymes.

Table 4: Aerobic decomposition of bioplastic

Source of bioplastic	Name of bioplastic	Environmental aspect	Condition	Biodegradation indicator	Time-consuming (days)
PLA based	PLA	Compost	58°C	Produce CO_2	60
	PLA	Compost	65 °C, pH= 8.5, humidity	Produce CO_2	58
	PLA	Compost	Aerobic, 58°C, 60% humidity	Wight loss	30
	PLA	Compost	55 °C, 70% moisture	Produce CO_2	28
	PLA	Compost	58°C	Produce CO_2	60
PAH-based	PHA	Soil/ Compost	25 °C, 65% humidity	Produce CO_2	15
	PHA	Compost	58 °C	Produce CO_2	90
	PHB	Compost	55 °C, 70% moisture	Produce CO_2	80
Starch-based	Bioplastic (potato)	Compost	Aerobic, 58 °C	Weight loss	28
	Master bioplastic (40% resin and 60% starch)	Compost	Aerobic, 23 °C, 55% moisture	Weight loss	90
	Cassava starch	Compost	Aerobic, 55 °C, 60% moisture	Weight loss	72
	Starch	Soil, Compost	25 °C	Produce CO_2	85
	Master bi-plastic carry bag	Compost	Soil Burial Test, room temperature	Weight loss	90
Cellulose-based	CA(produced from fiber flax)	Municipal solid waste mixture (compost)		Weight loss	14
	CA (produced from cotton linters)	Municipal solid waste mixture (compost)		Weight loss	14
	Sponge cloth from renewable resources, organic cotton mesh	Compost	1 m depth—15.7 °C average outside temperature	Weight loss	84
	Sponge cloth (Cellulose, Cotton mesh, Water, Salts, Pigments	Compost	1 m depth—15.7 °C average outside temperature	Weight loss	84
	Sponge cloth (70% Cellulose, 30% Cotton)	Compost	1 m depth—15.7 °C average outside temperature	Weight loss	84

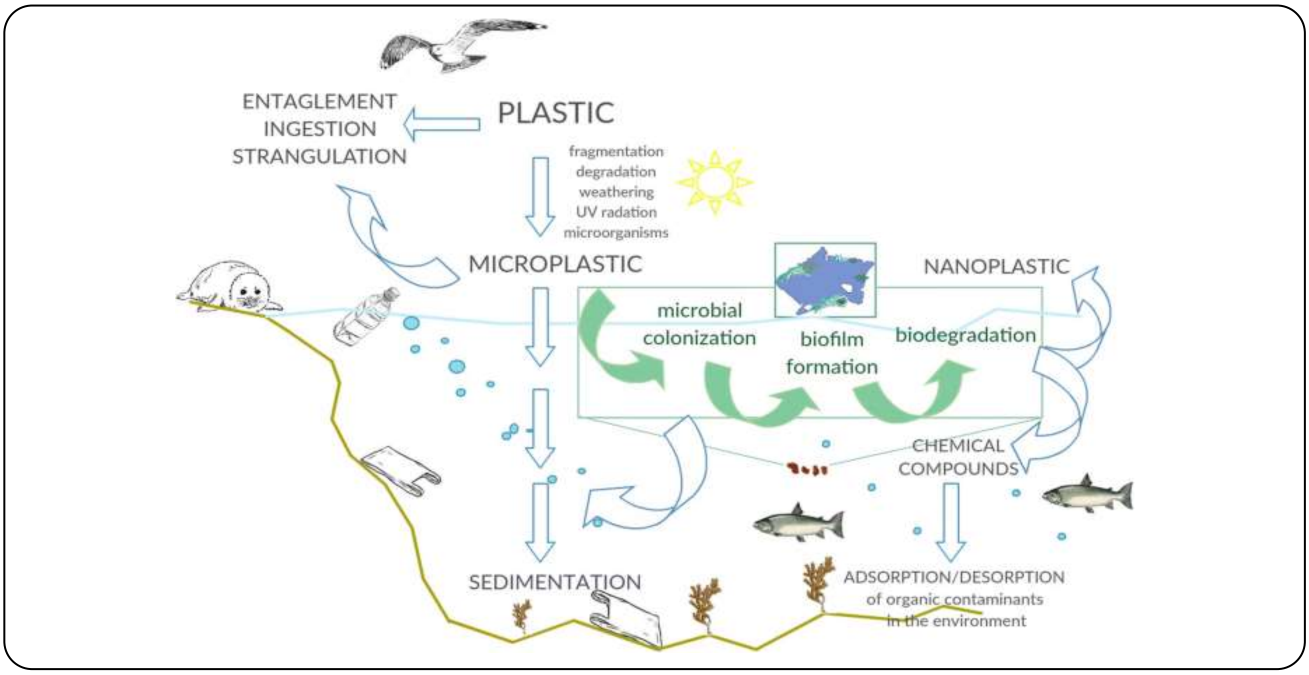

Fig.6: Bioplastic degradation process by micro-organisms in the marine environment. (Figure adapted from source [68]).

Table 5: Anaerobic decomposition of bioplastic.

Source of bioplastic	Name of bioplastic	Type of environment	Condition	Biodegradation indicator	Time-consuming (days)
PLA	PLA	Sludge	Anaerobic, 37 °C	Produced CO_2	277
	PLA	Sludge	Anaerobic, 55 °C	Produced CO_2	30-50
	PLA	AD	Anaerobic, 52 °C	Comparison to theoretical BMP	36
PHA	PHBs	AD	Anaerobic digestion—untreated PHB—35 °C	Conversion to biogas	175
	PHBs	AD	Anaerobic digestion—untreated PHB—35 °C	Conversion to biogas	175
	PHB	Sludge	Anaerobic, 55 °C	Produced biogas	14
Starch	Plastarch	AD	Anaerobic, 37 °C	Weight loss	23-30
	Mater-Bi plastic carrier bags	AD	Untreated bioplastic—35 °C	Weight loss	73
	Mater-Bi plastic carrier bags	AD	NaOH pre-treated bioplastic—35 °C	Weight loss	28-41

Furthermore, bioplastic help in keeping the anaerobic digester in ideal condition as the C/N ratio cannot be less than 15 but anaerobic decomposition is mostly bio-waste. The production of biogas, water, hydrogen sulfide, and ammonia is the main by-product of anaerobic digestion. Degradation of bioplastic in anaerobic conditions has some notable advantages over aerobic degradation of bioplastic e.g. limitation of odor and energy production [69]. Table 5 shows the anaerobic decomposition of bioplastic in various environmental conditions and times [69].

Organic matter + H_2O + Nutrients → Digestate + CH_4 + CO_2 + NH_3 + H_2S + Heat

COMMERCIAL APPLICATIONS OF BIOPLASTICS

Plastics and Bioplastic in packaging

In the modern era, bioplastic production has increased exponentially due to its eco-friendly and strategic nature with a rate of 750,000 tons/ year while petro-based plastic production is 200 tons/ year. The production of plastic is estimated to be about 1,000,000 tons/year in 2021[70]. For the last few decades, the food packaging sector was using conventional plastic for packaging due to its versatile properties. The increasingly adverse impacts of using conventional plastic in the environment lead to the emergence of an eco-friendly sustainable product i.e. bioplastic.

In the past centuries, people have used paper and cardboard (cellulose) as hardcover layers for external packaging. However, the role of paper and cardboard remains limited due to their opaque nature and poor resistance to moisture. After advancements in technologies, many versatile properties of bioplastic have been developed with different techniques such as casting, extrusion, thermo-modeling, sheeting, and blowing. Among the bioplastic, the casted film obtained from protein and carbohydrate as raw materials is highly resistant to oxygen due to the close packing of hydrogen bonding. Such type of bio-based plastic preserves staling properties under several temperature conditions and is used for packaging material to store vegetables such as broccoli, carrots, etc. Most of the conventional packaging materials are products of petrochemicals like PVC, PET, polystyrene (PS), polypropylene (PP), and polyamide (PA) [71]. Among these, PLA has been widely used [72,73]. The bio-based packaging material has certain parameters like water activity, pH, nutrients, oxygen, storage time, and temperature which control its stability. The only limitation of bioplastic in food packaging is the high oxygen and water vapor barrier. The hydrophilic character of the biodegradable starch-based film has low stability when exposed to different environmental conditions[74]. Table 6 shows the properties comparison of some common plastic with bioplastic.

Disposable Housewares

Disposable housewares made from biodegradable plastics are now seen as marketable options, replacing traditional plastics such as polystyrene and polyolefin. Housewares such as kitchen tools and utensils, washable storage containers and cups, bathroom accessories, toys,

Table 6: Properties comparison of some common plastic and bioplastic.

Polymer	Moisture permeability	Oxygen permeability	Mechanical properties
Cellulose	High- medium	High	Good
Cellulose acetate	Moderate	High	Moderate
Starch	High	Low	Good
Polyacetate	Moderate	High	Good
Low-density polyethyle	Low	High	Moderate
Polystrene	High	High	Poor-moderate

hangers and hooks are now being produced using biodegradable plastics. One such example is the Fantastic Beach toys by Zoe¨ b Organic made with Mirel bioplastic from corn. Cutlery made from Cereplast, a biodegradable resin made from corn and potato starch, qualifies as a compostable plastic and is marketed under the brand name Nat-Ur. Natur-Bag markets Natur-Ware cutlery which is both bio-based and certified compostable.

Agriculture and horticulture

Production of agricultural mulches, seeding strips, and tapes made from bioplastics is another strong potential market. The tape biodegrades in the soil as the seeds germinate and take root. Plastic mulch films are then used to give the new seedlings a head start in the spring; the mulch helps reduce evaporation and conserve moisture, increases soil temperature, and keeps control of the weeds. Compostable seed belts and active component capsulations made out of bioplastics have also proven to be beneficial. Foils and nets made from degradable bioplastics are used in the farming of mushrooms and the coating of tree and bush roots. Foils, yarns, and nets made out of bioplastics help to secure freshly created slopes and mounds and protect them from erosion until the roots of the plants have developed sufficiently. Solaplast mulching films are generally making rapid advances in this area. Solaplast 2100 series of resin applications in agriculture and horticulture include films for banana bushes and grapevine bushes which have to be protected from dust and environmental influences.

Medical devices

Nontoxic biodegradable bioplastics sutures are being used each year by surgeons in life-saving heart operations and other procedures. Easily sterilized, the sutures remain strong and intact until the surrounding tissues have healed. The sutures dissolve and are readily metabolized in the body leaving no trace. Both pliable braided sutures, as well as wiry monofilament sutures, are available, depending on (a) the type of surgery, (b) the knots to be used, (c) the tensile strength needed, and (d) the potential for infection. Plastic sutures are primarily made from lactic or glycolic acid and account for about 95% of the total market, with various pins, implants, and dental devices making up much of the remainder. Because of their biodegradability and linear release properties, these two systems are an excellent technology for the controlled release of proteins and small lipophilic molecules for local and systemic administration and have applications in pharmaceuticals and medical technology.

Consumer electronics

A large proportion of today's consumer market is made from plastics. In the electronics market, plastics are used in casings, circuit boards, and data storage because of their durability, toughness, lightness, and mobility. However, there has been a surge of bioplastic products introduced in the fast-moving consumer electronics sector such as touch screen computer casings, loudspeakers, keyboard elements, mobile casings, vacuum cleaners, and a mouse for a laptop. SUPLA has developed optimized PLA compounds for the consumer electronics industry based on lactides from Corbion Purac. The launching application is the world's first bioplastic touchscreen computer developed in collaboration with a Taiwanese OEM/ODM, Kuender. The high gloss housing of this computer is made from high-heat PLA.

Automotive

The automotive industry is going through a significant change focusing on reducing fuel consumption and emissions by reducing a vehicle's weight. Plastics have been a part of automotive components but there has been a concern about plastics recyclability. For this reason, the automotive industry is making a giant leap toward using bioplastic components. Some of the bio-based plastics are already successfully being used by leading automotive brands around the world today to reduce their product environmental impact. Bioplastics have reached maturity as a suitable material for many automotive applications, offering high performance and unique potential for reducing a product's environmental impact. Manufacturers have turned to bio-based or partly bio-based durable bioplastics to produce sturdy dashboard components as well as solid interior and exterior features. Components made completely or partially from bioplastics can provide a standard of safety that is of ultimate importance in the transportation sector. The products include seat and airbag covers as well as steering wheels.

ADVANTAGES OF BIOPLASTICS

In today's era, plastic is an essential commodity in our daily life. With the accelerating usage of conventional plastic, several environmental, as well as health issues, have increased tremendously resulting in the spoliation of soil, water, and air, which finally leads to global warming and an energy crisis[75]. Therefore, to mitigate such adverse outcomes and reduction in the utilization of conventional plastic, many researchers have suggested the use of bioplastics as they are eco-friendly and contribute less to environmental problems in various aspects. Some of the benefits of bioplastics are discussed below:

Fossil fuel consumption

Bioplastics are made from naturally occurring sources and deliberate a chance to reduce fossil fuel consumption by petrochemical plastics. The production of bioplastics also utilizes fossil fuel as an energy source for processing but not as the feedstock of petrochemical plastic, thus helping in the reduction of the consumption of fossil fuels. Nature Works and Matabolix are the two main manufacturing companies of PLA and PHB plastic. They claimed that on switching to bioplastics, the amount of fossil fuel consumption has been reduced to 68% from 98% respectively. As per concern, bioplastics do not utilize fossil fuel as raw material. If in case, bioplastics replace all the plastic worldwide, there will be a reduction in fossil fuel usage and eventually, it will save approximately 3.49 barrels in a day.

Carbon Emissions

The main benefit of the synthesis of bioplastics is that it emits less sequester of carbon dioxide into the atmosphere until it degrades. For the production of one kilogram of plastic from conventional fossil fuel, there is an emission of 3 kg of carbon dioxide for LDPE, 3.4 kilograms of carbon dioxide for PP whereas bioplastics like PLA and TPS produce only 1.8 kg and 1.14 kg of carbon dioxide. Plants used to make bioplastics absorb carbon dioxide and store it in the form of polysaccharides during their growth period.

Food supply

One of the major challenging problems for the synthesis of bioplastics is whether it affects the food supply or not. If the bioplastics are directly synthesized from crops like corn, soy, sugarcane other vegetables, it will potentially affect the food supply. However, bioplastics are synthesized from non-food plants like weeds, vegetable waste, and switch grass which impose a negligible effect on the food supply. Besides, many bioplastics like PLA are synthesized from sugar and sugar can be synthesized from different plants whereas thermoplastic is synthesized mainly from corn, and for 1kilo of TPS, 0.97 kilos of corn is needed. The U.S. government has provided agricultural land for cropping bioplastic crops to keep the global food market sustainable and undisturbed.

Pollution

In the production of bioplastics, there is less energy consumption and less carbon dioxide emission but it consumes even less when recycled again for further use. In general, bioplastics are easily recyclable as they are predominantly thermoplastic. The recycling process usually involves less energy consumption and less carbon dioxide emission for making a new product. Although, there is a problem with the recycling of bioplastics as their production limits to a less quantity, due to which a proper infrastructure for recycling is highly recommended.

Energy consumption

For the production of bioplastics, there is a requirement for less energy as compared to Petro plastics. The whole energy requirement for the production of PHB bioplastics is 44.7MJ per Kg plastic while there is a need for 85.9MJ per Kg polypropylene in the case of Petro plastic, however, they have the same characteristics. Among the bioplastics, PLA consumes more energy, and bioplastics such as TPS which are synthesized from starch consume less energy. Normally, starch base bioplastics consume energy ranging from 32.4 - 36.5MJ per kg.

Health

Until now, there is no report on the adverse effect of bioplastics on health. The monomer of bioplastics does not lead to any harmful effects as Petro plastic does and they degrade under the influence of microbe or some external environmental factors. However, some minor health issues arise in their production. People use pesticides and inorganic fertilizers for the cropping of bioplastic crops and this does have a chance to reach out and make water less suitable for drinking. The plasticizers of bioplastics may produce more toxicity than bioplastic, so it is wiser to understand that the safety of the bioplastics should be more considered. Plasticizers have been used in both bioplastics and petro plastic, although there is the use of hazardous plasticizers in the case of Petro plastic. However, in bioplastics, there is the use of some bio plasticizers like sorption, glycerine, etc. which imparts no such severe impact on health even though at their low concentration.

LIMITATION OF BIOPLASTICS

While biodegradable plastics have numerous advantages, they do have some drawbacks as well. Biodegradable plastics need specific conditions to decompose, meaning the natural breakdown of this plastic will not occur if sent to the landfill along with other waste. A special composting system is required to ensure the proper recycling/processing of biodegradable plastic bags. The other drawback to biodegradable plastics is that if they are not disposed of properly and mixed with regular plastics, they become contaminated and cannot be used anymore [76].

But, despite the minimal drawbacks of biodegradable plastic, it is still becoming a popular alternative to regular plastic, especially due to the growing awareness of environmental safety. Furthermore, the advantages of biodegradable plastics outweigh the disadvantages making them a better choice than plastic polymers that have been used traditionally.

CONCLUSIONS

This review has covered the basic concepts related to the field of Bioplastics, its type, the role of additives, degradation, advantages, and limitations of bioplastic in a concise manner. It can be revealed that the negative impact of petroleum plastic is adversely affecting the environment, and atmosphere and causing major health issues. An increase in the huge production of plastic creates many severe problems like the emission of carbon dioxide while extracting and combustion of waste plastic, and the processing of fossil fuel as plastic feed-stocks which directly or indirectly pollute the environment by emitting persistent organic pollutants in the environment like Furan, PCBs, short-chain chlorinated paraffin, Chlorinated dioxin, polybromodiphenyl increase health issues such as cancer, mental disorders, and reproductive and developmental disease problems. In India, only 28.4% of waste plastic is decomposed in an eco-friendly manner and the remaining quantities are disposed of in a landfill or open dumps.

Practically, Bioplastics can not be considered as the panacea of conventional plastics, but socially, economically, and eco-friendly, bioplastic is a sustainable plastic as compared with conventional plastic even though they produce greenhouse gases like ammonia, carbon dioxide, methane (in less quantity), etc. Currently, the percentage of bioplastic production contributes only 1% of global plastic production but a glimpse of huge potential could be seen in the upcoming era. With an advantage in technologies, the production of bioplastic from microorganisms through the biotechnology method gives innovation to compete for the current barrier and hazardous effects of other plastics. Bioplastics have many environmental profits like less energy consumption in production, fewer environmental problems, fewer health issues, less carbon dioxide emission, and are safe for consumption. Moreover, it has less carbon footprint as compared to conventional plastic. A bio-refinery concept also fits well into bioplastics as several high-value products can be obtained from a given feedstock/raw material/mixture. This whole makes them cost-effective. Hence, sustainability and eco-friendly bioplastic are deemed to create a safe environment. Additionally, it is finally recommended by the author concerning the literature suggesting advancements and eco-friendly outcomes of bioplastic that biodegradable bioplastic production from biomass as a raw material must be appreciably embraced and bioplastic may be a future the panacea of plastics pollution. ***"GREEN EARTH, CLEAN EARTH"***

Received : Jun. 1, 2021 ; Accepted : Oct. 11, 2021

REFERENCES

[1] Khosravi-Darani K., Yazdian F., Rashedi H., Madadian Bozorg N., Moradi M., Rezazadeh Mofradnia S., Simulation of Bioreactors for Poly (3-hydroxybutyrate) Production from Natural Gas, *Iran. J. Chem. Chem. Eng. (IJCCE)*, **39(1)**: 313–336 (2020).

[2] Spiegel S., Recent Advances in Applied Polymer Science., *Jr. App. Poly. Sci*., **135(24)**: 46279 (2018).

[3] Barra R., Leonard SA., Whaley C., Bierbaum R., Plastics and the Circular Economy, *Sci. Tech. Advis. Panel to Glob Environ Facil.*, **5**: 1–26 (2018).

[4] He M., Wang X., Wang Z., Chen L., Lu Y., Zhang X., Li Me., Liu Z., Zhang Y., Biocompatible and Biodegradable Bioplastics Constructed from Chitin via a "green" Pathway for Bone Repair, *ACS Sustain. Chem. Eng*., **5(10)**: 9126–9135 (2017).

[5] Thiruchelvi R., Das A., Sikdar E., Bioplastics as Better Alternative to Petro Plastic., *Mater. Today Proc.*, **37(2)**: 1634–1639 (2020).

[6] Maheshwari R., Rani B., Parihar S., Sharma A., Eco-Friendly Bioplastic for Uncontaminated Environment, *Res. Jr. of Chem. and Environ. Sci.*, **1(1)**: 44–49 (2013).

[7] Pernicova I., Enev V., Marova I., Obruca S., Interconnection of Waste Chicken Feather Biodegradation and Keratinase and Mcl-PHA Production Employing Pseudomonas Putida KT2440., *Appl. Food Biotechnol.*, **6(1)**:83-90 (2019).

[8] Coppola G., Gaudio MT., Lopresto CG., Calabro V., Curcio S., Chakraborty S., Bioplastic from Renewable Biomass: A Facile Solution for a Greener Environment., *Earth Syst. Environ.*, **2**: 1-21 (2021).

[9] Singh R.K., Ruj B., Plastic Waste Management and Disposal Techniques - Indian Scenario, *Int. J. Plast. Tech.*, **19(2)**: 211–226 (2015).

[10] Selvamurugan Muthusamy M., Pramasivam S., Bioplastics – An Eco-Friendly Alternative to Petrochemical Plastics., *Curr World Environ.*, **14(1)**: 49–59 (2019).

[11] Lebreton L., Anthony A., Future Scenarios of Global Plastic Waste Generation and Disposal, *Pal. Comm.*, **5(1)**: 1-11 (2019).

[12] Nielsen T.D., Hasselbalch J., Holmberg K., Stripple J., Politics and the Plastic Crisis: A Review Throughout the Plastic Life Cycle, *Wiley Interdiscip. Rev. Energy Environ.*, **9(1)**: 1–18 (2020).

[13] Mazhandu Z.S., Muzenda E., Mamvura T.A., Belaid M., Nhubu T., Integrated and Consolidated Review of Plastic Waste Management and Bio-Based Biodegradable Plastics: Challenges and Opportunities, *Sustain.*, **12(20)**: 1–57 (2020).

[14] Reddy R.L., Reddy V.S., Gupta G.A., Study of Bio-plastics as Green & Sustainable Alternative to Plastics, *Inter. Jr. of Emer. Tech. and Adv. Eng.*, **3(5)**: 76–81 (2013).

[15] Favaro L., Basaglia M., Rodriguez J.E.G., Morelli A., Ibraheem O., Pizzocchero V., Casella S., Bacterial Production of PHAs from Lipid-Rich by-Products., *Appl. Food Biotechnol.*, **6(1)**: 45-52 (2019).

[16] Brigham C.J., Riedel S.L., The Potential of Polyhydroxyalkanoate Production from Food Wastes, *Appl. Food Biotechnol.*, **6(1)**: 7-18 (2018).

[17] Thakur S., Chaudhary J., Sharma B., Verma A., Tamulevicius S., Thakur V.K., Sustainability of Bioplastics: Opportunities and Challenges, *Curr. Opin. Green Sustain. Chem.*, **13**: 68–75 (2018).

[18] Winfield IJ., Plastic Soup: an Atlas of Ocean Pollution, *J. Fish. Biol.*, **95(2)**: 686–686 (2019).

[19] Muhammad Shamsuddin I., Bioplastics as Better Alternative to Petroplastics and Their Role in National Sustainability: A Review, *Adv. Biosci. Bioeng.*, **5(4)**: 63 (2017).

[20] Proshad R., Kormoker T., Islam MS., Haque MA., Rahman MM., Mithu MMR., Toxic Effects of Plastic on Human Health and Environment : A Consequences of Health Risk Assessment in Bangladesh, *Int. J. Heal.*, **6(1)**: 1 (2017).

[21] Rosen MA., Kishawy HA., Sustainable Manufacturing, and Design: Concepts, Practices and Needs, *Sustainability*., **4(2)**: 154–174 (2012).

[22] Parveen G., Bashir S., Thakur A., Saha S.K., Banerjee P., Kumar A., Experimental and Computational Studies of Imidazolium Based Ionic Liquid 1-methyl- 3-Propylimidazolium Iodide on Mild Steel Corrosion in Acidic Solution Experimental and Computational Studies of Imidazolium Based Ionic Liquid 1-methyl-3-propylimidazolium, *Mater. Res. Express.*, **7(1)**: 016510 (2020).

[23] Bashir S., Thakur A., Lgaz H., Chung IM., Kumar A., Corrosion Inhibition Efficiency of Bronopol on Aluminium in 0.5 M HCl Solution: Insights from Experimental and Quantum Chemical Studies, *Surfaces and Interfaces*, **20**: 100542 (2020).

[24] Bashir S., Thakur A., Lgaz H., Chung I-M., Kumar A., Corrosion Inhibition Performance of Acarbose on Mild Steel Corrosion in Acidic Medium: An Experimental and Computational Study, *Arab. J. Sci.*, **45**: 4773-4783 (2020).

[25] Bashir S., Thakur A., Lgaz H., Chung I-M., Kumar A., Computational and Experimental Studies on Phenylephrine as Anti-Corrosion Substance of Mild Steel in Acidic Medium, *J. Mol. Liq.*, **293**: 111539 (2019).

[26] OECD. Considerations and Criteria for Sustainable Plastics from a Chemicals Perspective, *OECD. Glob. Forum. Environ. Plast. a Circ. Econ.* (May): 1–58 (2019).

[27] El-malek F.A., Khairy H., Farag A., Omar S., The Sustainability of Microbial Bioplastics, Production and Applications, *In.t J. Biol. Macromol.*, **157**: 319–328 (2020).

[28] Momani B.L., Assessment of the Impacts of Bioplastics : Energy Usage, Fossil Fuel Usage, Pollution, Health Effects, Effects on the Food Supply, and Economic Effects Compared to Petroleum Based Plastics, *Assessment of the Impacts of Bioplastics: Energy Usage* ., (March) (2009).

[29] Ferreira R., Renata S., Ferreira C., Reinert O., Gandolfi R., Brito L., Characterization of Starch-Based Bioplastics from Jackfruit Seed Plasticized with Glycerol., *J. Food. Sci. Technol.*, **55(1)**: 278–286 (2017).

[30] Koller M., Linking Food Industry to "Green Plastics"–polyhydroxyalkanoate (PHA) Biopolyesters from Agro-Industrial by-Products for Securing Food Safety, *Appl. Food Biotechnol.*, **6(1)**: 1-6 (2019).

[31] Cinelli P., Mallegni N., Gigante V., Montanari A., Seggiani M., Coltelli M.B., Bronco S., Lazzeri, A., Biocomposites Based on Polyhydroxyalkanoates and Natural Fibres from Renewable Byproducts., *Appl. Food Biotechnol.*, **6**(1):35-43 (2019).

[32] Zhong Y., Godwin P., Jin Y., Xiao H., Biodegradable Polymers and Green-Based Antimicrobial Packaging Materials: A Mini-Review, *Adv. Ind. Eng. Polym. Res.*, **3(1)**: 27–35 (2020).

[33] Tsang YF., Kumar V., Samadar P., Yang Y., Lee J., Song H.., Production of Bioplastic Through Food Waste Valorization, *Environ. Int.*, **127**(March): 625–644 (2019).

[34] Fatimah N., Sultan K., Lutfi W., Johari W., The Development of Banana Peel / Corn Starch Bioplastic Film: A Preliminary Study, *Bio, Sci, Tech.*, **5(1)**: 12-17 (2017).

[35] Muthuraj R., Misra M., Mohanty AK., Injection Molded Sustainable Biocomposites from Poly(butylene succinate) Bioplastic and Perennial Grass, *ACS Sustain. Chem. Eng.*, **3(11)**: 2767-2776 (2015).

[36] Padil VVT., Senan C., Agarwal S., Varma RS., Bioplastic Fibers from Gum Arabic for Greener Food Wrapping Applications, *ACS Sust. Chem. Eng.*, **7(6)**: 5900-5911 (2019).

[37] Cardona CA., Orrego CE., Paz IC., The Potential for Production of Bioethanol and Bioplastics from Potato Starch in Colombia, *Fruit, Veg, Cer, Sci, Biotech.*, **3**: 102-114 (2009).

[38] Starch G., Plasticizer S.A.S., Sariningsih N., Putra Y.P., Pamungkas W.P., Amri A., Bioplastic from Chitosan and Yellow Pumpkin Starch with Castor Oil as Plasticizer Bioplastic from Chitosan and Yellow Pumpkin Starch with Castor Oil as Plasticizer., *Mat. Sci. Eng.*, **333(1)**:1–8 (2018).

[39] Bilo F., Pandini S., Sartore L., Depero L.E., Gargiulo G., Bonassi A., A Sustainable Bioplastic Obtained from Rice Straw, *J. Clean. Prod.*, **200**: 357–368 (2018).

[40] Maheswari NU., Ahilandeswari K., Production of Bioplastic Using Spirulina Platensis and Comparison with Commercial Plastic., *Res. Environ. Life Sci.*, **4(3)**: 133-136 (2011).

[41] Cifriadi A., Panji T., Wibowo N.A., Syamsu K., Bioplastic Production from Cellulose of Oil Palm Empty Fruit Bunch Bioplastic Production from Cellulose of Oil Palm Empty Fruit Bunch, *Ear. Environ. Sci.*, **65(1)**: 012011 (2017).

[42] Wang K., Mandal A., Ayton E., Hunt R., Zeller M. A., Sharma S., Modification of Protein Rich Algal-Biomass To Form Bioplastics And Odor Removal, *Pro. Byprod.*, **1**: 107-111 (2016).

[43] Fathanah U., Lubis M.R., Nasution F., Masyawi M.S., Characterization of Bioplastic Based from Cassava Crisp Home Industrial Waste Incorporated with Chitosan and Liquid Smoke, *Ear. Environ. Sci.*, **334(1)**: 012073 (2018).

[44] Patel A.V., Panchal T., Thomas M., "Preparation and Characterization of Biodegradable Packaging Film Using Groundnut Protein Isolate", *24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands*, (2016).

[45] Kartika T., Harahap M.B., Ginting M.H.S., Utilization of Mango Seed Starch in Manufacture of Bioplastic Reinforced with Microparticle Clay Using Glycerol as Plasticizer, *Mat. Sci. Engin.*, **309(1)**: 012068 2018

[46] Aziz I.A., Wan C., Robiah S., Adollah R., Fibre Based Bioplastic Film from Morus Sp. (mulberry) Leaves for Medical Purpose Fibre Based Bioplastic Film from Morus Sp. (mulberry) Leaves for Medical Purpose, *Jr. Phy.: Conf. Ser.*, **1372(1)**: 012069 (2019).

[47] Shellikeri A., Kaulgud V., Yaradoddi J., Ganachari S., Banapurmath N., Shettar A., Development of Neem Based Bioplastic for Food Packaging Application Development of Neem Based Bioplastic for Food Packaging Application, *Mat. Sci. Eng.*, **376(1)**: 012052 (2018).

[48] Revadhi T., Nanthini R., Biosynthesis of Polyhydroxybutyrate from Giant Reed Grass Hydrolysate and Evaluation of its Drug Releasing Profiles., *Jr. of Drug Del. and Thera.*, **9**: 8–15 (2019).

[49] Lim J., Hii S., Chee S., Wong C., Sargassum siliquosum J . Agardh Extract as Potential Material for Synthesis of Bioplastic Film, *Jr. App. Phyc.*, **30(6)**: 3285-3297 (2018).

[50] Hempel F., Bozarth AS., Lindenkamp N., Klingl A., Zauner S., Linne U., Microalgae as Bioreactors for Bioplastic Production, *Agris*, 2–7 (2011).

[51] Luengo J.M., García B., Sandoval A., Naharro G., Olivera ER, Bioplastics from Microorganisms, *Curr. Opi. Micro.*, **6(3)**: 251-260 (2003)

[52] Ibrahim M.H.A., Lebbe L., Willems A., Steinbüchel A., A New Thermophile for Bioplastic Synthesis: Comparative Phylogenetic and Physiological Study, *AMB Express*, **6(1)**: 1-9 (2016).

[53] Quill F., Ullah A., Vasanthan T., Bressler D., Elias A.L., Wu J., Bioplastics from Feather Quill, *Biomacromol.*, **12(10)**: 3826-3832. (2011).

[54] Author S.J., Sharma U., Goswami G., Bio-Plastic from Waste Newspaper, *Int. Jr. Res. Eng. Tech.*, **2(30)**: 1-12 (2018)

[55] Moura I.G. De., Sá A.V. De., Sofia A., Machado L., Vera A., Machado A., Bioplastics from Agro-Wastes for Food Packaging Applications, *Food. Pack.*, **1**: 223-267 (2017).

[56] Varna E., Yakar S., Demir M., Possibilities of Bioplastics Production from Fish, *Verslas. Tech. Biomedicin. Inovac. Įžvalg.*, **1(10)**: 533–539 (2019).

[57] Marturano V., Cerruti C., Ambrogi V., Polymer Additives, *Phy. Sci. Rev.*, **2(6)**: 0130 (2016).

[58] Iqbal N., Khan A.S., Asif A., Yar M., Haycock J.W., Rehman I.U., Recent Concepts in Biodegradable Polymers for Tissue Engineering Paradigms: A Critical Review, *Int. Mater. Rev.*, **64(2)**: 91–126 (2019).

[59] Ambrogi V., Carfagna C., Cerruti P., National I., Marturano V., Additives in Polymers, *Mod. Poly. Comp.*, **1**: 23-26 (2017).

[60] Poon J., Madden D.C., Wood M.H., Clarke S.M, Characterizing Surfaces of Garnet and Steel, and Adsorption of Organic Additives, *Langmuir*, **34(26)**: 7726-7737 (2018).

[61] Innes A., Associates FR., Marietta M., Specialties M., Compounding Metal Magnesium Hydroxide and ATH Flame Retardants Require, *Plas. Add. Comp.*, **1**: 22–26 (2002).

[62] Bhattacharya R.R.N., Chandrasekhar K., Roy P., Khan A., Challenges and Opportunities: Plastic Waste Management in India., *Ener. Resource Inst.*, **1** (2018)

[63] Jadhav SD., Jhabarmal J., A Review of Non-Halogenated Flame Retardant, *Pharma. Innov. J.* **380(5)**: 380–386 (2018).

[64] Zhao C., Zhou Y., Zhao C., Bao C., Cracking Processes and Coalescence Modes in Rock-Like Specimens with Two Parallel Pre-Existing Cracks, *Rock Mech. Rock Eng.*, **51(11)**: 3377-3393 (2018).

[65] Fillers F., Gmbh WV., Isbn W., Part One Polymers and Fillers., *Func. Fill. Plas.*, **1**: 12-16 (2010).

[66] Hobbs CE., Recent Advances in Bio-Based Flame Retardant Additives for Synthetic Polymeric Materials, *Poly.*, **11(2)**: 224 (2019).

[67] Frache FBA., Taskin AFE., Edoardo PSC., Fate of Biodegradable Polymers under Industrial Conditions for Anaerobic Digestion and Aerobic Composting of Food Waste, *J. Polym. Environ.*, **28(9)**: 2539-2550 (2020).

[68] Urbanek A.K., Rymowicz W., Mirończuk A.M., Degradation of Plastics and Plastic-Degrading Bacteria in Cold Marine Habitats, *Appl. Microbiol. Biotechnol.*, **102(18)**: 7669–7678 (2018).

[69] Folino A., Karageorgiou A., Calabr PS., Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review, *Sustain*., **12**: 1–37 (2020).

[70] Gironi F., Energy Sources, Part A : Recovery, Utilization, and Environmental Effects Bioplastics and Petroleum-Based Plastics : Strengths and Weaknesses, *Ener. Sour.*, **33(21)**: 1949-1959 (2011).

[71] Mangaraj S., Yadav A., Bal LM., Dash SK., Mahanti NK., Application of Biodegradable Polymers in Food Packaging Industry: A Comprehensive Review, *J. Packag. Techno.l Res.*, **3(1)**: 77–96 (2019).

[72] Rahman R., Sood M., Gupta N., Bandral J.D., Bioplastics for Food Packaging : A Review, *Int. Jr. Curr. Micro. App. Sci.*, **8(03)**: 2311–2321 (2019).

[73] Kumar Y., Shukla P., Singh P., Prabhakaran .PP., Tanwar VK., Bio-Plastics : A Perfect Tool for Eco-Friendly Food Packaging : A Review., *Jr. of Food Prod. Develop. Pack.*, **1**: 1–6 (2014).

[74] Jabeen N., Majid I., Nayik GA., Bioplastics and Food Packaging : A Review Bioplastics and Food Packaging : A Review, *Cogent. Food. Agric.*, **42(1)**: (2015).

[75] Gonçalves de Moura I., Vasconcelos de Sá A., Lemos Machado Abreu A.S., Alves Machado A.V., Bioplastics from Agro-Wastes for Food Packaging Applications, *Food Pack.*, **1**: 223-263 (2017).

[76] Sidek I.S., Draman S.F.S., Abdullah S.R.S., Anuar N., Current Development on Bioplastics and Its Future Prospects: an Introductory Review, *INWASCON. Technol. Mag.*, **1**: 03–08 (2019).