International Journal of Biotechnology and Microbiology
www.biotechnologyjournals.com
Online ISSN: 2664-7680, Print ISSN: 2664-7672
Received: 22-10-2025, Accepted: 21-11-2025, Published: 06-12-2025
Volume 7, Issue 4, 2025, Page No. 66-71

Bio-plastic: A possible substitute for traditional polymers

Dr. Ankita D Suvagiya*, Neha J Nanvani, Naval Sevra, Naimish Chauhan, Kajal Ghodadra
Assistant Professor, Faculty of Science, Noble University, Junagadh, Gujarat, India

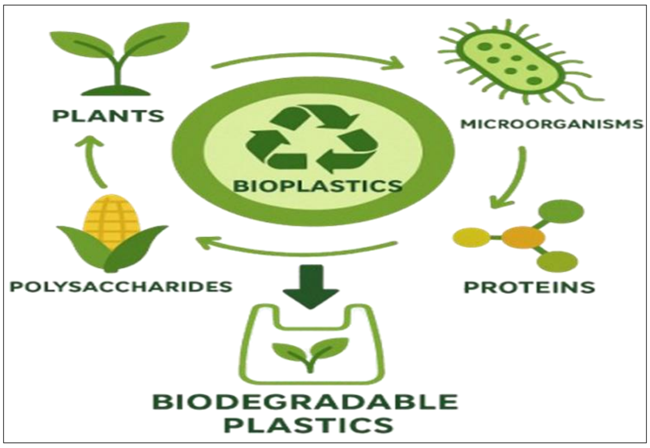
Abstract
Biomaterials refers to synthetically irrelevant products that are produced by microorganisms (or a portion of them) in a variety of ecological parameters. Bioplastics are a noteworthy category of biomaterials. Biodegradable polymers are essentially polyesters that have characteristics with petrochemical plastics and are present intracellularly in microbes as storage granules. Bioplastics come from a variety of sources, including proteins, polysaccharides, microbes (polyhydroxyalkanoates, or PHAs), plants (plastics based on cellulose and starch), and plants. Microbial plastics (PHAs) are particularly interesting among them since they are biocompatible, biodegradable, and nontoxic. Many prokaryotic bacteria, parasitic species, and algae are capable of producing these polyesters. *Pseudomonas aeruginosa, P. oleovorans, P. stutzeri,* and *Bacillus megaterium* are a few examples of bacteria that produce PHA. From a biotechnological standpoint, bioplastics are extremely exciting because most of them are biodegradable and biocompatible. This chapter provides an overview of the present state of the use of bioplastics in India, their many sources, recycling, environmental effects, and the merits and cons of doing so are all covered.

Keywords: Polyesters, biodegradable, storage granules, bioplastics

Introduction

Plastics are used in almost every industry, including packaging, consumer goods, transportation, electrical wiring, building construction, hardware, and contemporary equipment. Plastics are composed of from organic components such as coal, cellulose, salt, combustible gas, and, of course, unprocessed petroleum. Before being used, unrefined petroleum needs be managed because it is a complex mixture of hundreds of different substances. In a petroleum processing facility, raw petroleum is first refined in order to create polymers. This separates the heavy, unprocessed petroleum into divisions, which are collections of lighter segments. Every division consists of a blend of hydrocarbon chains, which are synthetic compounds made up of hydrogen and carbon. The particles in these chains differ in size and shape. Naphtha is one of these components and the key ingredient needed to make plastics.

In general, there are numerous types of plastics, such as thermoplastics which becomes softer when heated and harder when cooled, such as polyethylene and thermosets, which never get softer once they have formed [1]. In recent years, petroleum-based plastic has been widely used, and its barrier to biodegradation has created a serious biological problem for the because solid wastes contain hydrocarbons, a non-renewable basic element, their organization has exacerbated environmental damage and climatic changes. When we discard these plastic items after using them, they are discovered floating on rivers or lying exactly where we threw them for days, years, or more. Therefore, it is estimated that by 2050, there will be more plastic bottles in rivers than fish if we do not recycle these plastic materials [2]. These plastics were also broken down into valuable items like fuels using a variety of processes (hydrocracking, pyrolysis, catalytic degradation), but these also produced harmful gasses that resulted in the creation of goods composed of bio-plastics [3]. Then, due to its nontoxicity, sustainability, biocompatibility, and biodegradability, bio-plastic has gained more attention globally as a substitute for produced plastics claimed that several renewable raw resources (polysaccharides and proteins), plants (starch-based and cellulose-based plastics), and other components can be used to create biodegradable polymers. Polyhydroxyalkanoates (PHAs) are microbiological bioplastics [4]. PHAs are the most promising type of bioplastic; they have characteristics with regular polymers and are nontoxic, biodegradable, and biocompatible. PHAs are variously structured biopolymers that function as a defensive system for long-term stressors with nutritional imbalance. PHA accumulates inside bacterial cells as stored energy, indicating a restricted food supply [5]. Numerous prokaryotic bacteria, which are found inside cells or cytoplasm as water-insoluble granules of 0.2 to 0.5 µm, as well as micro-algal and parasitic species, are capable of producing these polyesters. Examples of bacterial species include *Bacillus* The microbes *P. megaterium, P. oleovorans, P. aeruginosa*, and *P. stutzeri* have been examined for their ability to produce PHA. Additionally, the bacterial cells are protected from osmotic stress conditions by the granular form of these PHA. As is well known, monomers and polymers (like starch) are also components of bio-plastics. Researchers also call these C and H monomers in it "carbonosomes." Therefore, we may alter the form, color, and flexibility of these polymers to suit our needs by changing their arrangement. Further claimed that PHAs are appropriate biopolymers for a variety of applications due to their wide range of unsaturated bond or functional group changes, from methyl to tridecyl, and chain length. Lots of applications. PHB (polyhydroxy butyrate), which is likewise created by microorganisms and has extra characteristics including air impermeability, water insolubility, and thermoplastic nature, is one PHAS. Polymeric science research is very interested in using PHAs to create bio-plastics because of their effectiveness and maintainability in achieving the practical improvement goals set out by the United Nations [7].



Graphical Abstract

What makes plastic problematic?

Plastic contamination or pollution is the accumulation of plastic objects and particles (such as plastic jugs, bags, and microbeads) in the environment that negatively affects natural life. Polymers that act as pollutants are divided into three size categories: micro-, meso-, and macro-debris. Because plastics are durable and affordable, people are producing a lot of them. Most plastics are delayed in degrading because of their material design, which makes them resistant to many common cycles of degradation. When combined, these two factors have led to a highly noticeable level of plastic pollution in the atmosphere. Water and land bodies can become contaminated by plastic. Between 1.1 and 8.8 million metric tons of plastic debris are thought to enter the ocean annually through waterfront networks. Living organisms, predominantly marine life, can be harmed by mechanical impacts, such as being caught or twisted in plastic objects, problems linked to consuming plastic trash, or exposure to synthetic substances found in plastics that alter their physiology. Around 380 million tons of plastic are produced annually worldwide as of 2018. It is estimated that 6.3 billion tons of plastic were shipped worldwide between 1950 and 2018, of which 9% was recycled and the remaining 12% was burned. This massive 90% of seabird groups are thought to contain plastic rubbish, according to studies suggesting that plastic pollution enters the climate. There have been significant efforts in some areas to reduce the level of free-roaming plastic pollution by reducing plastic use, cleaning up litter, and promoting plastic reuse.

Bioplastics

Bioplastics are made from renewable biomass sources, such as wood chips, corn starch, vegetable fats and oils, leftover food scraps, and more. By-products from farming can be used to make bioplastic and also, from used plastic bottles and various compartments that use microbes. Basic plastics, such as non-restorable energy source plastics (also known as Petro-based polymers), are made from gasoline. Not all bioplastics decompose naturally. Bioplastics are mostly derived from sugar by products such as lactic acid, cellulose, and starch.

Types of Bioplastic

Starch-based plastics

Currently accounting for around half of the bioplastics market, thermoplastic starch is the most widely used bioplastic you may also make basic starch bioplastic at home. Pure starch is a suitable substance for the creation of medicine cases by the drug area since it may absorb humidity. Plasticizer and flexible, that is for example, sorbitol and glycerine can be added to the starch to enable thermoplastic preparation. By adjusting the amounts of these additional ingredients, the properties of the resulting bioplastic (also known as "thermo-plastic starch") can be tailored to meet particular needs. Decomposable polyesters are commonly combined with starch-based bioplastics to deliver starch/polycaprolactone or starch/Eco flex (BASF-created polybutylene adipate co-terephthalate) mixed [7]. These mixtures can be composted and are used in mechanical applications. Like Roquette, a number of producers have created alternative starch/polyolefin mixes. Compared to oil-based plastics used for comparable purposes, these blends have a smaller carbon footprint but are not biodegradable [8]. Celluloid and its derivatives, such as cellulose esters (including nitrocellulose and cellulose acetic acid derivative), are the main components of cellulose bioplastics.

Bio-derived polyethylene

Ethylene is the basic building block (monomer) of polyethylene. It is possible to obtain ethylene, which is synthetically comparable to ethanol, by fermenting or aging plant feedstock. For instance, maize or a sugar stick. Synthetically and actually identical to regular polyethylene, bio-inferred polyethylene is reusable even though it doesn't biodegrade. Additionally, bio induction of polyethylene can effectively reduce emissions of substances that deplete the ozone layer.

Genetically altered bioplastics

Similarly, genetically modified organisms (GM) are a test for the bioplastics industry. Currently, open or accessible bioplastics, which are rather unique, necessitate the use of genetically modified crops, despite the fact that GM The typical feedstock is corn. In the future, some of the technologies being developed to produce bioplastics of the second era will use the "plant factory" paradigm, enhancing efficiency through the use of genetically modified crops or microbes.

Some aliphatic polyesters

The majority of the polyhydroxyalkanoates (PHAs) found in aliphatic bio polyesters include polyhydroxy valerate (PHV), poly-3-hydroxybutyrate (PHB), and polyhydroxy hexanoate (PHH).

Poly-3-hydroxybutyrate (PHB)

Polyester, the biopolymer PHB, is produced by particular tiny organisms that break down glucose or maize starch. Its properties are similar to those of polypropylene, a petroleum-based plastic. The PHB production process involves growing. For example, the sugar sector in South America has decided to expand PHB production to a contemporary level. PHB is mostly viewed based on its authentic qualities [9]. Additionally, it is biodegradable without development and has a liquefying point greater than 130 °C. It also prefers to form a transparent or simple film.

Polyhydroxyalkanoates (PHA)

PHAs, or polyhydroxyalkanoates, Straight polyesters known as polyhydroxyalkanoates are produced naturally when bacteria break down sugar or lipids. The bacteria make them in order to store energy and carbon. In industrial manufacturing, the conditions for sugar maturation are advanced in order to extract and purify the polyester from the microorganisms. Within this family, more than 150 different monomers can be combined to create materials with a wide range of characteristics. In addition to being biodegradable, PHA is less rigid and more malleable than other plastics *(*Qu *et al.*, 2006*)* [20]. The therapeutic sector makes extensive use of these polymers.

When bacteria are under stress, they must consume a sugar or carbon source (Table 1), digest it, and then release plastic as PHA because PHAs are compounds that store carbon and energy. PHA is created by polymerizing it when nutritional supplies are unbalanced (depletion of N2, P, or O2). A culture of a microbe, like *Cupriavidus necator*, is put in the right medium and given the right nutrients to grow quickly.

Table 1: Different Carbon and microbial Sources for PHAs production

Carbon Source	Microbial Strain	References
Rice Bran	*Pseudomonas hydrogenator*	Koller *et al.*, 2008 [9]
Starch	*Ralstonia eutropha*	Raza *et al.*, 2018 [12]
Apple Pulp Water	*P. citromellolis*	Rebocho *et al.*, 2019 [11]
Soybean Oil	*P. aeruginosa*	Hori *et al.*,2002 [14]
Glucose	*R. eutropha*	Tsang *et al.*, 2019 [13]

Structure of PHA

PHAs are spherical granules with a diameter of 0.1 to 0.2 µm. They have a molecular weight of 2×106 Dalton units and are collected in the cytoplasm. Additionally, a phospholipid monolayer surrounds them (Fig. 2), which offers integrity or serves as a protective barrier against dangerous chemicals. PHA monomers unite to produce a biopolymer, meaning that each monomer is the same and that the polymer is created when they do so. The melting point will rise in proportion to the number of C atoms in the side chain.

Biosynthesis of PHA (Poly hydroxyalkanoates)

Polyhydroxyalkanoates (PHAs) are a class of biodegradable and biocompatible polyesters synthesized by various microorganisms as intracellular storage materials. They serve as carbon and energy reserves and are produced mainly under conditions of excess carbon source and limited essential nutrients such as nitrogen, phosphorus, or oxygen. PHAs are considered environmentally friendly alternatives to petroleum-based plastics due to their biodegradability and renewability. The most common type of PHA is polyhydroxy butyrate (PHB). PHAs are stored in bacterial cells as granules and can be extracted for industrial use. The key microorganisms capable of producing PHAs include *Cupriavidus necator* (formerly *Ralstonia eutropha*), *Bacillus megaterium*, *Alcaligenes latus*, *Azotobacter vinelandii*, and *Pseudomonas putida*. These bacteria can use various carbon substrates such as glucose, sucrose, molasses, fatty acids, and even industrial or agricultural waste materials. The biosynthesis of PHAs occurs through a well-defined enzymatic pathway, especially in the case of PHB production. The process begins with the conversion of carbon sources into acetyl-CoA, a key metabolic intermediate. The biosynthetic pathway involves three main enzymes:

1. **β-Ketothiolase (Phi):** Catalyzes the condensation of two molecules of acetyl-CoA to form acetoacetyl-CoA.
2. **Acetoacetyl-CoA reductase (PhaB):** Reduces acetoacetyl-CoA to (R)-3-hydroxybutyryl-CoA using NADPH as a cofactor.
3. **PHA synthase (PhaC):** Polymerizes (R)-3-hydroxybutyryl-CoA into PHB, which accumulates as granules inside the bacterial cell.

PHAs have wide industrial applications due to their thermoplastic properties and biodegradability. They are used in packaging, agriculture (mulch films, seed coatings), and biomedical fields (sutures, drug carriers, tissue engineering). However, high production costs remain a challenge. Research is ongoing to improve yield and reduce costs using genetically engineered strains and inexpensive substrates such as agro-industrial waste. In conclusion, the biosynthesis of PHAs is a microbial strategy to cope with environmental stress and an important process for sustainable bioplastic production. Advances in metabolic engineering and fermentation technology are expanding the potential for large-scale and cost-effective PHA production [16].

PHA Purification and Extraction

The extraction of PHAs as they are formed within the cell is one of the key processes to obtain PHAs in a purified state. The researchers used novel methods for their extraction, such as genetic recombinants. For example, temperature-sensitive mutations occur when *Escherichia coli* reacts to a signal such as an increase in temperature. The cell is destroyed as a result, and the PHAs leak into the culture medium. The two phases used in aqueous two-phase interaction are the non-volatile phase and the water phase. Therefore, the organic component flows in the non-volatile whereas the non-organic component settles in water. In this instance, the finished product also contained contaminants. Initially, the extraction process used the freeze-drying or lyophilization method. Later, methylene chloride and chloroform were used to help with the extraction process. Methylene chloride aids in while other lipid cells disintegrate in chloroform, PHAs precipitate out of the solution. PHAs are also extracted by enzymatic digestion, in which the effectiveness of enzymes such as protease in triggering cell lysis has been evaluated. Because they are more cost-effective and inflict less harm on the final product, mechanical disruption via bead milling or high-pressure homogenization techniques are also employed [17].

Techniques involving bioengineering to produce these PHAs

Advances in genetics, biotechnology, manufacturing science, and metabolic design have given scientists the ability to control and improve cellular and molecular processes. Paths through biochemistry to obtain attractive results since it is now possible to create synthetic mixes in excess or to dispose of them entirely using such sophisticated and intricate processes. Synthetic biotechnology increases the pace at which PHA synthases are biosynthesised, hence improving catalytic activity Matsumoto *et al.*, 2006 [19]. Cost-effective proteins called hasins are also employed to remove PHB without causing any disruption to other cell components. Certain microorganisms have been modified to begin generating these PHAs, including as the yeast *Yarrowia lipolytica*. Similarly, the E. coli genes min C and min D have the ability to divide several times instead of binaryly, which may be utilized to increase PHB synthesis in this case [18].

Effects on the environment

Since there are different definitions of "greenness" (such as water use, energy use, deforestation, biodegradation, and so forth), the natural impact of bioplastics is thought to be questionable. Additionally, the dispute is complicated. Because there are so many different kinds of bioplastics, each with unique environmental advantages and disadvantages, only one bioplastic out of every few can be regarded as equal. The creation and usage of bioplastics is occasionally seen as a more viable activity in relation to the amalgamation of Petro plastics because it uses fewer fossil fuels during manufacturing and produces fewer net-new greenhouse emissions if it biodegrades. Compared to oil-based plastics, which have a long shelf life, the usage of bioplastics may result in less hazardous waste [19].

When the majority of bioplastics are produced or synthesized, less carbon dioxide is released. However, there is worry over a faster rate of deforestation and soil erosion as compared to conventional alternatives erosion and negative impact on water sources in order to establish a worldwide bio economy and generate massive amounts of bioplastics. A worldwide bio economy would need to be managed carefully.

The biodegradation of bioplastics

There are instances where the terminology employed in the bioplastics field is deceptive. The term "bioplastic" is used by the majority of businesses to refer to plastic that is derived from a biological source. Everything (oil and bio-based). The fact that plastics are biodegradable suggests that, in the right circumstances, they can undergo biodegradation [27]. However, because they break down so slowly, many of them are regarded as non-biodegradable. Because they are thought to be biodegradable, certain petrochemical-based plastics can be added to commercial bioplastics to improve their performance. Temperature, oxygen content, and polymer stability are the variables influencing bioplastics' capacity to biodegrade.

EN13432, a European standard provided by the European Composting Unit, describes the standard pace and degree of plastic breakdown under the strictly regulated and aggressive conditions (at or above 140 °F) of an industrial composting unit. In order to be perceived as the International Organization for Standardization biodegradable. However, it doesn't outline a guideline for composting at home. Most bioplastics do not biodegrade quickly in a regular fertilizer heap or in soil or water; instead, they only biodegrade in industrial composting facilities, with the exception of starch-based bioplastics, which biodegrade under normal composting circumstances [20].

Because of its apparent ability to biodegrade, manufacturers also classify the specially modified petrochemical-based plastics as "biodegradable plastic." Unless the maker stabilizes it with the expansion of stabilizing Ultraviolet (UV) light, chemicals, and oxygen can also cause conventional plastics like polyethylene to degrade [29]. Degradable plastic, also known as photodegradable plastic, is a controlled UV/oxidation deterioration that can be treated by adding a degradation initiator to the stabilized plastic. This process isn't initiated by microbial activity. The EN13432 commercial composting requirements are not met by these biodegradable materials, which is why oxo biodegradable plastics are criticized [21]. The ASTM standard is used as a guide by manufacturers of oxo-biodegradable plastics, which are ordinary petroleum-based products with specific additional ingredients that initiate decomposition. P-Life is an Oxo-plastic, which is reportedly biodegradable in soil at 23°C, drops to 66% after 545 days [30].

Recycling

Bioplastics raise a number of issues, including the possibility that they would damage already-existing recycling initiatives. For example, packaging like HDPE milk bottles and PET water and soda bottles are easily identifiable and although reusing and establishing a recycling foundation have been effective in many parts of the world, only 27% of all plastics are really reused. However, since PET and PLA do not mix, consumers may fail to distinguish between the two when sorting, which could result in an unsuitable recycled PET. The solution to this problem is to invest in appropriate sorting technology, which is also quite expensive, or to guarantee specific bottle kinds [26]. Recycling plastic is the largest issue since it requires a lot of work. This is a result of the sorting process's difficulties in being automated. Sorting the containers is simple because they are typically made from a single kind of plastic, but sorting other plastic products—like cell phones, which typically have parts composed of various plastic types becomes problematic [22].

New research and development initiatives are underway to increase the recycling rates of plastic items and enhance methods for sorting or dismantling them. Nevertheless, aside from expensive polymers like since virgin polymer, which is made from a waste product in the oil refining process, is so readily available and inexpensive, there is no real economic or environmental justification for costly sorting equipment [25]. The same amount of oil would be extracted even in the absence of plastics. Thermal recycling is the method used in Germany to turn waste plastics into electricity.

The advantages of employing bioplastics include

Many of the largest consumer merchandise companies in the world have begun using bioplastics in the packaging of their products throughout the last five years. Models include Nestle's use of a bioplastic top for their Brazilian milk products, Proctor and Gamble's bioplastic shampoo packaging, and Coca-Cola's use of a blend of regular plastic and bioplastic in their soda containers. Coca-Cola's Plant Suppress uses 30% plant-based ingredients and oil PET. The bottle can be recycled in the same way as other PET containers at the current reuse offices. Coca-Cola aims to use According to Scott Vitters, the company's director of sustainable packaging, bottles that are "made with 100% plant-waste material while remaining totally recyclable" enhanced "printability," or the ability to print an image or text on plastic that is incredibly readable. Compared to regular plastics, bioplastics can be made to have a significantly more respectable surface feel with "a less 'oily' feel." The likelihood of giving the item in a plastic holder a different taste is reduced. For example, milk in a styrene cup will taste different, but the bioplastic option has no such effect [28]. The water fume porosity of a bioplastic may be significantly higher than that of a conventional plastic. This can be inconvenient in some situations, like when packing sandwiches, but given the freshly made bread. A bioplastic holder will be very helpful in releasing excess steam or fume. For uses like packaging for cosmetics, a bioplastic's softer and more tactile feel might be very advantageous to customers. Although bioplastics are opaquer, they can be made clearer and more translucent [23].

Drawbacks

The global food crisis is exacerbated by competition for food sources brought on by growing interest in bioplastics. This is a false argument that is frequently made in opposition to bioplastics. The raw ingredient used to make bioplastics is an assessment of industrial quality maize that wasn't created with humans in mind. It is now possible to create biodegradable bioplastics from hemp, seaweed, and other plants thanks to recent revolutionary advancements in the bioplastics industry. We may anticipate seeing a lot of new creative products as the industry grows. People are encouraged to trash more by bioplastics [24].

Conclusion

Bioplastics have emerged as a promising and sustainable alternative to conventional petroleum-based plastics. Derived from renewable biological sources such as starch, cellulose, vegetable oils, and microbial fermentation products like polyhydroxyalkanoates (PHAs) and polylactic acid (PLA), bioplastics offer key advantages—biodegradability, lower carbon footprint, and reduced environmental pollution. With growing awareness of plastic-related hazards and stricter environmental regulations, the demand for eco-friendly materials is on the rise. However, bioplastics are not without limitations. Challenges such as high production costs, lower mechanical strength compared to traditional plastics, limited raw material availability, and compatibility with existing recycling systems must be addressed. Despite these constraints, current research and technological innovations are steadily enhancing the performance and scalability of bioplastics. Looking to the future, the development of next-generation bioplastics will focus on improving thermal stability, mechanical strength, and biodegradation rates. Genetic engineering of microbes for high-yield PHA production and utilization of waste biomass and agricultural residues as cost-effective feedstocks are key areas of focus. Integrating biorefinery approaches, where bioplastics are co-produced with biofuels or other valuable biochemicals, can improve economic viability. Moreover, policy support, investment in green technologies, public awareness, and global collaboration will be crucial to accelerate the adoption of bioplastics. With growing consumer demand for sustainable materials, bioplastics have the potential not only to partially replace traditional plastics but also to transform the global plastic economy into a more circular, environmentally responsible system. In conclusion, while bioplastics alone may not be a complete solution to plastic pollution, they are a significant step toward reducing environmental impact and promoting a sustainable future.

Reference

1. Urbanek AK, Rymowicz W, Mirończuk AM. Degradation of plastics, plastic-degrading bacteria in cold marine habitats. Applied microbiology, biotechnology,2018:102(18):7669-7678.
2. Băhnăreanu C. World economic forum 2019: globalization 4.0–A better version. Strategic Impact,2019:(72-73):79-82.
3. Muneer F, Rasul I, Azeem F, Siddique MH, Zubair M, Nadeem H, *et al*. Microbial polyhydroxyalkanoates (PHAs): efficient replacement of synthetic polymers. Journal of Polymers, the Environment,2020:28(9):2301-2323.
4. Mostafa YS, Alrumman SA, Alamri SA, Otaif KA, Mostafa MS, Alfaify AM, *et al*. Bioplastic poly-3-hydroxybutyrate production by the marine bacterium Pseudodonghicola xiamenensis through date syrup valorization, structural assessment of the biopolymer. Scientific reports,2020:10(1):8815.
5. Chien PJ, Sheu F, Yang FH. Effects of edible chitosan coating on quality and shelf life of sliced mango fruit. Journal of food engineering,2007:78(1):225-229.
6. Dietrich CF, Bamber J, Berzigotti A, Bota S, Cantisani, V, Castera L, *et al*. EFSUMB guidelines and recommendations on the clinical use of liver ultrasound elastography, update 2017 short version. Ultraschall in der Medizin European Journal of Ultrasound,2017:38(04):377-394.
7. Chen GQ, Patel MK. Plastics derived from biological sources present future a technical, environmental review. Chemical reviews,2012:112(4):2082-2099.
8. Defoirdt T, Boon N, Sorgeloos P, Verstraete W, Bossier P. Alternatives to antibiotics to control bacterial infections luminescent vibriosis in aquaculture as an example. Trends in biotechnology,2007:25(10):472-479.
9. Koller M, Bona R, Chiellini E, Fernandes EG, Horvat P, Kutschera C, *et al*. Polyhydroxyalkanoate production from whey by Pseudomonas hydrogenovora. Bioresource technology,2008:99(11):4854-4863.
10. Raza A, Razzaq A, Mehmood SS, Zou X, Zhang X, Lv Y, *et al*. Impact of climate change on crops adaptation strategies to tackle its outcome: A review. Plants,2019:8(2):34.
11. Rebocho AT, Pereira JR, Freitas F, Neves LA, Alves VD, Sevrin C, *et al*. Production of medium-chain length polyhydroxyalkanoates by Pseudomonas citronellolis grown in apple pulp waste. Applied Food Biotechnology,2019:6(1):71-82.
12. Hori M, Eades J, Hayano RS, Ishikawa T, Pirkl W, Widmann E, *et al*. Direct Measurement of Transition Frequencies in Isolated p¯ H e+ Atoms, <? format?>, New CPT-Violation Limits on the Antiproton Charge, Mass. Physical review letters,2003:91(12):123401.
13. Tsang A, Xie F, Xin X. Foreign institutional investors, corporate voluntary disclosure around the world. The Accounting Review,2019:94(5):319-348.
14. Chien CC, Chen CC, Choi MH, Kung SS, Wei YH. Production of poly-β-hydroxybutyrate PHB by Vibrio spp. isolated from marine environment. Journal of Biotechnology,2007:132(3):259-263.
15. Defoirdt T, Halet D, Vervaeren H, Boon N, Van de, Wiele T, *et al*. The bacterial storage compound poly-β-hydroxybutyrate protects Artemia franciscana from pathogenic Vibrio campbellii. Environmental microbiology,2007:9(2):445-452.

16. Dietrich K, Dumont MJ, Del Rio LF, Orsat V. Producing PHAs in the bioeconomy—towards a sustainable bioplastic. Sustainable production and consumption,2017:9:58-70.
17. Endres HJ. Bio-based thermoplastic, thermosets polymer. In Lightweight, sustainable materials for automotive applications. CRC Press, 2017, 139-166.
18. Koller M. Biodegradable, biocompatible polyhydroxy-alkanoates PHA auspicious microbial macromolecules for pharmaceutical therapeutic applications. Molecules, 2018:23(2):362.
19. Matsumoto KI, Aoki E, Takase K, Doi Y, Taguchi S. In vivo and in vitro characterization of Ser477X mutations in polyhydroxyalkanoate PHA synthase 1 from Pseudomonas sp. 61− 3: Effects of beneficial mutations on enzymatic activity, substrate specificity, and molecular weight of PHA. Biomacromolecules,2006:7(8):2436-2442.
20. Qu XH, Wu Q, Zhang KY, Chen GQ. In vivo studies of poly 3-hydroxybutyrate-co-3-hydroxyhexanoate based polymers biodegradation tissue reactions. Biomaterial,2006:27(19):3540-3548.
21. Sudesh K, Iwata T. Sustainability of biobased and biodegradable plastics. CLEAN Soil, Air, Water,2008:3 6(5-6):433-442.
22. Urbanek AK, Rymowicz W, Mirończuk AM. Degradation of plastics and plastic-degrading bacteria in cold marine habitats. Applied microbiology and biotechnology,2018:102(18):7669-7678.
23. Friesen E. The world economic forum and transnational networking. Emerald Publishing Limited, 2020.