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Review Article

Bioplastic an alternative to plastic in modern world: A systemized review

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ABSTRACT

Currently, plastic pollution is one of the biggest environmental concerns, and sustainable alternatives to traditional plastics are being explored. Using bioplastics, which are made from renewable resources and biodegradable, can reduce plastic pollution and promote environmental sustainability. This review article examines the role of bioplastics in today's society as alternative plastics. A variety of biodegradable polymers, including PLA, PHA, PBS, SB, CB and PUH, have been tested. Plastics made from bioplastics can be used in a wide range of industries, including packaging, biomedical devices, agriculture, and 3D printing. Despite tremendous advances, difficulties such as scalability, cost competitiveness, and end-of-life management remain, requiring additional research and innovation. For the development and implementation of bioplastic alternatives on a global scale, collaboration between academia, business, and governments is essential. Using bioplastics can reduce plastic pollution, greenhouse gas emissions, and promote a more sustainable future. In order to address the challenges of plastic pollution in the 21[st] century, it is important to switch to biodegradable and ecologically friendly materials.

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INTRODUCTION

One of the biggest problem of our's era is pollution and responsible for millions of death every year. Addition of any harmful material that reduce the environment's natural quality, causing adverse effects on ecosystem, or provide a health risk are considered as pollution [1]. Pollution comes from diverse sources, both natural like volcano eruption [2], forest fires [3], biogenic emission [4], dust storm [5], methane emission [6] and human activities e.g., industrial activities [7], transportation [8], agricultural practices [9], waste management [10], domestic use [11]. Pollution caused from these sources vary region to region but according to reported literature natural sources contribute 30% of global fine particular matter (PM 2.5) while rest 70% caused by human activities [12]. Similarly, 40% of global methane emission caused by natural sources and human activities contribute rest 60% [13]. Depending on the nature of pollutants, pollution is mainly classified as:

Air Pollution

Release of any pollutant into air is known as air pollution mainly caused by industrial emission (gasses like SO_2, NO_x, volatile organic compounds, particulate matters and heavy metals) [7], transportation (CO, NO_2) [14], agricultural activities (crop burning and using fertilizers release a large amount of NH_3, CH_4, CO_2, N_2O, SO_2, NO_x, VOC) [15], urbanization (rapid rise of industries, buildings, roads, waste treatments, residential heating or cooling produce high amount of SO_2, CO_2, Particulates, NO_2, and CO) [16], and

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natural sources (dust, ash, smoke, volcano eruption, forest fires and physical disasters release SO_2, NO_x, VOC, polycyclic aromatic hydrocarbons) [1]. Air pollution can lead not only many respiratory diseases like asthma, chronic obstructive pulmonary disease and high risk of lung cancer [17] but also cause cardiovascular diseases like hypertension, heart attack, stroke, atherosclerosis, systematic inflammatory responses, thrombosis, arrhythmia and vasoconstriction [18]. It also cause Alzheimer's disease, Parkinson's disease, chronic brain inflammation, multiple sclerosis, white matter abnormalities, microglia activation [19] and effect reproductive system as well [20]. Air pollution is the major factor for climate change [21], global warming [22], acid rain [23] and increase soil acidity [24].

Water Pollution

Water is the most important nutrient necessary for life of all ages [25]. Contamination of harmful chemicals to waterbodies including ocean, rivers, lakes and ground water due to industrial discharges mainly release heavy metals, ammonia, urea, phenolic compounds, perfluroalkyl acids, NaOH, hydrogen peroxide, formaldehydes, perfluorooctanoic acid [26], agricultural runoff that discharge animal waste, fertilizer, pesticides, herbicide, fungicide, [27], high amount of heavy metals [28], municipal wastewater [29] and mining [30] is called water pollution.

Water pollution is the major environmental pollution which leads more than 50 diseases and 50% child death annually [29]. According to world water development (WWD), every year 2–2.5 million people died due to diarrhea, 10 million deaths from cancer, 80,000 rectal cancer alone in US, 9.3% deaths from digestive cancer, 36,000 people from dengue, caused by poor water quality [29]. Except this, alone in Bangladesh 35 million people daily exposed to arsenic in drinking water [31]. Similarly, in Pakistan both ground water and surface water is mainly effected by pesticides, coliforms and toxic metals [32]. As reported by UNESCO in 2021, 80% industrial and municipal water is transferred into environment without treatment [29]. Industrial polluted water contains heavy amount of arsenic, lead, vinyl chloride and benzene, responsible for mutation, DNA damage, tumor, liver cancer, reproductive cancer, and gastric cancer [33, 34].

Soil Pollution

Soil is the mixture of organic matter (dead living organism), minerals, air and water, play important role for plant growth, food production and support life on earth [35]. Contamination of hazardous compounds in soil, which has a negative impact on ecosystem, human health and on agricultural productivity, produced by industrial activities released transition metals (lead, cobalt, zinc, chromium, nickel, cobalt, iron) [36], petroleum hydrocarbons, pesticides, biological pathogens [37], sulphate ions [38]; mining activities mainly produce toxic metals (mercury, lead, arsenic, cadmium, copper, chromium) [39, 40]; agricultural practices like fertilizer, pesticide, herbicide, animal waste release uranium, lead, radium, phosphates, nitrates and persistent organic pollutants [41]. Soil pollution cause soil erosion, degradation of ecosystem, loss of soil fertility, affect plant growth, contaminate drinking water and disturb aquatic habitat [42].

Plastic Pollution

Environmental pollution is the major problem of the modern times and plastic is one of the leading cause. Plastic has played a significant role in our lives but our ecology is in danger due to its excessive use [43]. More than one third of the total mass of plastics produced globally is used to make packaging, which is typically not recycled and ends up as waste. The excessive use of plastics has a considerable negative influence on the environment over time; it is estimated that 34 million tons of plastic are manufactured year, but only 7% of it gets recycled, with the other 93% being dumped into landfills and the ocean [44]. The materials that we commonly refer to as plastics are high molecular mass, synthetic organic polymers, primarily derived from hydrocarbons obtained from crude oil and natural gas [45]. The two main types of plastic are thermoplastic and thermoset [46]. The thermoplastic category includes materials like (high and low density) polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS), as well as "expanded polystyrene," while the thermoset category includes materials like polyurethane (PUR) and epoxy resins or coatings. When heated, thermoplastic can be repeatedly molded, whereas thermoset cannot be heated and remolded once it has been created. Plastics are typically generated from fossil fuels, but biomass (such as maize or plant oils) is being used more and more in their production. Once a polymer is synthesized, its properties remain the same regardless of the type of raw material used (i.e. PE will have the same properties, whether it is made from ethylene derived from fossil or biological sources) [47].

Plastic is mainly divided into different types among them single-use-plastic (SUP) is most common, important and widely used almost 50% of total plastic, used in packaging, bottles, bags, straws and cutlery, utensils [48, 49]. SUP contain bisphenol A, and persistent organic pollutants (POP) cause reproductive disorder, chronic diseases, developmental issue, immune system damage and endocrine disruption [50]. Another type of plastic is microplastic, tiny plastic particles having size less than 5mm, most toxic due to small size can be ingested and stored easily [51]. Microplastic mainly PS, PP, PE are used as microbeads in face wash, toothpaste, body wash, facial scrubs, cosmetics, and medical products, cause intestinal inflammation, asthma, oxidative stress, DNA damage, metabolic disorder, organ dysfunction, neurotoxicity and cancer [52–54].

Petroleum-based plastics have negative effects on the environment and society since they are not biodegradable and can release carcinogens when damaged or heated [55]. PVC [56] and PE [57] were two accidentally discovered new forms of plastics. In the early 1900s, formaldehyde and phenol were combined to create the first totally synthetic thermosetting glue, which Leo Baekeland dubbed Bakelite [58].

According to a rough estimation in 2019, 370 million tons annually produced and is continuously increasing that will be 445.25 million tons, among this more than 90% plastic cannot be recycled [59, 60]. Plastic is the biggest threat for environment, effect marine life [61], kill seabirds [62], contaminating aquatic ecosystem [63], affect plant fertility [64], respiratory health issue [65], climate change [45], release toxic gases [66] and increase carbon emission [67].

Over 99% plastic produced from non-renewable sources like fossil fuel [67], however researchers are now working on plastic production from renewable sources known as biodegradable plastic.

Bioplastics

Plastic prepared from plant or animal material is commonly known as bioplastic [68]. In pre-20th century people used cellulose, rubber and lignin extracted from grasses, agricultural waste, natural plant fiber and wood [69]. Bakelite and cellulose acetate were the 1st synthetic polymers prepared from natural sources with some chemical modifications in early 20th century for sunglasses, home furnishes, electronic devices, dresses, whistles, slip covers, cameras, and in some weapons [70]. In 20th century bioplastic like polylactic acid and polyhydroxyalkonates gained attention due to their cheapness, easy use and durability [71]. 2000–2010 was the commercialization period of bioplastic and many companies like NatureWork LLC produced bioplastics on large scale for stencils, biomedical applications and packaging [72].

Bioplastic also known as biodegradable plastic or biodegradable polymer, currently a new type of plastic, eco-friendly, cheap, degradable and recyclable, used mainly for packaging [73]. Bioplastic is mainly categorized into bio-based bioplastic and petroleum-based bioplastic [74].

Polyhydroxybutylate (PHB), the first bio-based bioplastic discovered in 1925 [75]. Except it, polyethylene succinate (PES), polyhydroxyalkonate (PHA), polybutyl succinate (PBS), polyethylene tertraphosphate (PET) and polyethylene furanoate (PEF) are other bio-based plastics commonly used [73]. Bio-based bioplastic can be synthesized by using waste biomass like jackfruit [76], waste banana peels [77], organic waste [78], agriculture waste [79], newspaper waste [80], oil palm empty fruit bunch [81], sugar cane [82], corn starch [83], potato starch [80], rice straw [84], rapeseed oil [85], cellulose and lignin from plants [86], bacteria [87], and Nano-fiber [88]. This bioplastic is easily degraded from bacteria [89–91], algae, and fungi [92], further both anaerobic/aerobic settings can facilitate the decomposition of bioplastics [93].

Petroleum based bioplastic, on the other hand is not degradable but can be prepared from petroleum or fossil fuels with some modification or addition of additives that facilitate faster degradation as compared to traditional plastic [94].

Properties of Bioplastic

Bioplastic is considered as unique, environmental friendly and attractive alternative to traditional plastic due to its properties. These properties vary depend on the composition of bioplastic. Some important properties of bioplastic are:

Biodegradability

Bioplastic can easily be degraded by enzymatic action, physical action, chemical reaction. Except these, bioplastic can easily be degraded by microbial action like aerobics, an-aerobics, archaebacterial, photosynthetic bacteria, fungi, present in soil, water at different environmental conditions (25–60°C, 50%–60% humidity and 7–8 pH) [95]. Due to this unique property bioplastic is best use as compared to petroleum plastics that retain in environment for hundreds of years.

Flexibility and Durability

Bioplastics are flexible and durable, can easily be bended, deformed and change shape without breaking [96] when exposed to mechanical stress, environmental effect, chemical exposure, UV radiation, pressure, temperature and aging factor [97]. This is an important property that enhance its application in different industries (packaging, medical devices, textiles and agriculture) to increase shelf life and decrease environmental impacts [98].

Transparency

Transparency is an important property when bioplastics are used in packaging, disposable items, or thin films [99]. Starch-based, cellulose-based, sugar-can-based and PHA are more transparent, can pass light without absorption or scattering [100]. Due to their transparency, these are widely used in food industry, labs, pharmaceuticals, electronics and automobiles [101].

Heat resistance

The ability of bioplastic to resist at high temperature without deformation, damaging or changing shape is called heat resistance of bioplastic, a crucial property when using in packaging, electronics and automobile components [102]. Starch-based bioplastics have more heat resistance (96.7 °C) than PLA (50–60 °C) [103].

Types of Bioplastics

As, bioplastic is plastic produced by renewable sources alternative to conventional plastic, today a wide variety of bioplastics are used, these types depend on source (raw material).

- Polysaccharides-based bioplastic
- Protein-based bioplastic
- Some aliphatic polyesters

Polysaccharides-Based Bioplastic (PSB)

These bioplastics are gaining popularity as sustainable alternatives to standard petroleum-based polymers due to low environmental effect and can be prepared by using natural material like cellulose, starch and chitin etc.

Starch Bioplastics (SB)

The second-largest agricultural product is starch. Currently, 2050 million tons starch produced from cereal and 679 million tons from roots annually [104] and 50% of bioplastic yearly produced from starch [105].

For conversion of starch into bioplastic, gelatinization is the important step, that involves heating of starch material with water so that granules absorb water, the H-bonds within the granules are ruptured to distort crystalline structure, after absorbing water starch molecules swell, become viscous or jelly like material [106]. Sometime plasticizers like sorbitol, glycol, and glycerol are added to enhance bioplastic characteristics [107]. The ratio of amylose to amylopectin significantly affects the characteristics of starch bioplastic. Higher amylose starch often has better mechanical qualities [108].

However, high moisture, gelatinize temperature, starch type (amylose concentration), plasticizer and time effect the property as well as use of bioplastic [109]. To increase mechanical properties and biodegradability of bioplastics PLA, PBS, PCL, PHA, PBAT are blended with starch [110]. SB are commonly used as packaging material due to low cost [111, 112].

Cellulose Bioplastics (CB)

Cellulose production is approximately 180 billion tons around the globe [113] and its bioplastic production will be 5.33 million tons in 2026 [114]. Cellulose bioplastic can be prepared by agricultural byproducts, pulp, softwood trees, plant material (rich in cellulose), bacteria, algae, fungi etc., [113]. The main components of cellulose bioplastics are cellulose ester like cellulose acetate, cellulose butyrate, nitrocellulose [115].

Polymerization is the most important step for bioplastic formation, cellulose monomers are joined to form polymer (cellulose ester) by using acetic anhydride or acetic acid [113]. CB show excellent biodegradability (40% degraded in five days) [116], high tensile strength, low density, low permeability [117], but can mix with PHA, PLA to improve mechanical properties, flexibility, non-toxicity, biodegradability and processing characteristics [118]. Such bioplastics are widely used in pharmaceutical, food, cosmetic, thermoplastic and automobile industry [119].

Protein Bioplastic (PB)

Different proteins from plant or animal source like casein, gluten, soy, collagen, can be used to produce bioplastics [120]. PB mainly used for packaging films and coating [121].

Some Aliphatic Polyesters

Aliphatic polyesters are frequently used due to versatility, biocompatibility, can be prepared from plant feedstock or microbial fermentation and are derivatives of aliphatic diols and dicarboxylic acids like PHA, PHB, PHV, PHH, PLA, PHU, PBS, PET. Small description of each is given below

Polylactic Acid (PLA)

PLA a glowing material synthesized by polymerization of lactic acid from starch, corn cassava, sugar beet or sugarcane via fermentation [122]. Due to its properties like good mechanical strength, biocompatibility, eco-friendly and biodegradability, these are used in 3D printing, medical devices, textile, packaging and disposable items [123].

Polyhydroxyalkanoates (PHA)

PHA can synthesize naturally by a variety of microbes, including those that ferment carbohydrates or fats [124]. In the natural world, microbes digest sugar or fats to form linear polyesters known as PHA. PHA is biodegradable and has characteristics that make it less elastic and more ductile than other polymers and have wide range of applications in biomedical, agriculture and food industry [125].

Polyethylene Terephthalate (PET)

Ethylene glycol (EG) and terephthalic acid (TPA) polymerize to form the polymer known as PET. PET is thermoplastic and contain 70% EG +30% TPA [126]. Although PET is primarily derived from fossil fuels and is not biodegradable but increase biodegradability and low cost PET can be synthesized from bio-based material like plant feedstock.

Due to low cost, transparency, and biodegradability PET is widely used as beverage bottles, food containers, straws, storage box [127]. PET accounts for over 16% of all plastic used in packaging in Europe.

Polybutylene Succinate (PBS)

PBS, also known as polytetramethylene succinate, is a thermoplastic polymer resin that belongs to the polyester family. An aliphatic polyester that is biodegradable and has qualities similar to polypropylene. One easy way to prepare PBS, a flexible semi-crystalline polymer, is to simply esterify succinic acid with 1,4-butanediol [128]. Nowadays, fermentation is used to produce succinate mostly from renewable resources. PBS is similar to petro-plastic due to flexibility, thermal stability, strength, and low cost make them highly useful in packaging films, agriculture (mulch films), automobile components, shopping bags [129].

Polyhydroxyurethanes (PHU)

According to studies, PHU sometimes is not considered as bioplastic but a synthetic plastic contains –NHCOO- (urethane linkage) produced by the reaction of polyols and isocyanates. Polyols can also be derived from renewable sources like plants oil, therefore it can also be known as bioplastic [130, 131]. Due to some properties like biodegradability (ability to break into small components by microbial action), mechanical properties (flexibility, elasticity, cannot deform easily), thermal stability (heat resistance), chemical resistance (resist to certain chemicals and solvents), cost, water absorption and biocompatibility PHU is considered better as compared to commercial plastics [132, 133]. PHU is excellent candidate for drug delivery system.

Poly-3-Hydroxybutyrate (PHB)

PHB is the type of bioplastic formed from plant starch/sugar by microbial action via fermentation [134]. PHB have low thermal stability, high degree of crystallization, non-toxic and commonly used in packaging, biodegradable, biocompatible, autocatalytic nature, easily recycled, low cost, improved mechanical behavior and thermoplastic [135].

Application of Bioplastics

As, bioplastic is biocompatible produced from renewable and biodegradable resources. Its production is continuously growing, has a wide range of applications due to their non-toxic nature, easy availability, biodegradation, flexibility and durability. These are widely used in our daily life now days in food container, packaging, kitchen ware, bottles, straws etc. Some significant applications are mentioned below:

Packaging

330 million tons annually plastic is produced world-wide and its 40% is consumed for packaging. Bioplastics have found widespread use in packaging materials for drinks, food and consumer goods, offering comparable characteristics to conventional plastics but originating from renewable sources [136, 137]. The main advantages to use bioplastics for packaging are to preserve food nutritional components, stop food decay and increased the shelf life of foods [138]. For packaging different types of bioplastics like PLA (films, straws, lids, pouches, bags, wrappers, pills, capsule, green house films) derived from plant source [139–141], PHA (food container, wraps, beverages, dairy products, cosmetics, seed covers, crop films) originate from bacterial fermentation of sugar or lipids [142–144], PBS (Packaging films, bags, trays, bottles) prepared by succinic acid and 1,4-butanediol [145] and starch-based (Food wrappers, shopping bags, trash bags, disposable cutlery, tableware) [111, 112].

Textile

The use of textile fiber is increased 100 million metric tons and continuously increasing as papulation increased; with natural fiber it is impossible to cover such a big consumption [146]. Bioplastics can be processed into fibers and commonly used in textile, alternative to synthetic fiber [137]. Improved breathability, reduced environmental influence, light weight, easy modifications like coloring, bleaching, cheapness and non-effectiveness against mice or other insects, PHA and PLA alone or their blends with natural fibers like jute, cotton, bamboo and widely used for clothes, carpets, non-woven fabrics [147, 148].

Agriculture

A number of benefits can be gained from the use of bioplastics in agriculture, including the reduction of carbon footprint. Biodegradable bioplastics, for example, degrade more rapidly and naturally, emitting organic molecules without harming the environment. Bioplastics are commonly used as mulch films [149] (to control weeds growth, maintain soil moisture, enhance crop quality), greenhouse films (control temperature and UV protection), seedling pots [150], seed coating [151] (increase germination rate, protection, control nutrients).

Medical and Drug Delivery

Due to environmental friendly nature, biocompatibility and biodegradability bioplastics like PGA, PLA, PHA, PLGA, PCL, PLLA and PCLA are used in medical for making surgical instruments [152], syringes [117], gloves, cups, trays and wound dressing [153].

Bioplastics are gaining attention in drug delivery system (DDS) due to their properties. Different bioplastics like PLGA converted into microparticles, nanoparticles [154]; chitosan into hydrogels [155]; cellulose biopolymers into films, coating [156]; and PHA into microspheres or nanoparticles [157] to encapsulate drugs.

Cosmetics

Nowadays, Biopolymers also used in Cosmetics and beauty products such as thickeners, conditioners, binders, active Ingredients and sensory materials. PHAs are commonly used material in cosmetology, although its production is expensive but they are mix with other biopolymers such as starch or PLS to make less expensive [137].

Electronics

Bioplastics like PHA (making electronic components), PCL (making flexible components, phototypes, sensor) and PEF (producing complex electronic components, pack electronic devices, improve mechanical support to devices) [158].

3-D Printing

Bioplastic has practical applications in 3D printing like in medical sector to design medical devices, anatomical models, and customized prostheses. PLA, PCL, PLGA due to non-toxic nature used in medical applications, tendon and skin regeneration [159, 160]

Automobile Industry

As, an alternative to petroleum based plastic bioplastic is used for making internal automobile components [161] (dashboards, storage components, headrests, automotive seats), engine components [162] (fuel lines, electronic connectors), CB due to light weight used as external automobile components [162] (bumpers, door trims, body panels) [119].

CONCLUSION

In conclusion, bioplastics are a sustainable and environmentally friendly alternative to traditional plastics. We've highlighted a variety of biodegradable polymers for 3D printing, packaging, and biomedical devices that are biodegradable. In contrast to conventional plastics, bioplastics are renewable and biodegradable. Additionally, bioplastics are improving mechanical properties and expanding their applications due to advancements in technology. Despite significant progress, bioplastics still face challenges, such as scalability, cost-effectiveness, and end-of-life management. In order to overcome these obstacles and to promote widespread adoption of bioplastics, further research and innovation are needed. In order to facilitate the transition to a circular economy, academia, industry, and policymakers must collaborate. Using bioplastics reduces plastic pollution, mitigates climate change impacts, and promotes sustainability. Aside from preserving our ecosystems, bioplastic alternatives can also improve the resilience of our planet and safeguard our future generations.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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