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Review Article

Biowaste to Bioplastics: An Ecofriendly Approach for A Sustainable Future

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Abstract
Bioplastics are biodegradable polymers of biological origin. The exhausting fossil resources and ever increasing environmental pollution caused by plastics derived from these resources is driving the growth of the bio plastic industry. There is increasing focus on developing low cost and durable bio based plastics, with a wide range of applicability. Currently, a majority of raw material for bioplastics production comes from agricultural crops, which indirectly poses threat to food security. Hence using organic wastes from biological origins, will not only limit our dependency on agricultural crops, but may also assist in solid waste management, in an effective manner. Industries, particularly food and agriculture sector, produce significant amounts of organic wastes, which can be harnessed for this purpose. It will also reduce the cost of production to a remarkable extent. Hence, this review focuses on the types of bio based plastics and gives an insight on biological wastes that can be utilized to produce such plastics. It is indeed, the need of time to intensify innovations and research in this field to overcome the hindrances and developing viable processes for manufacturing bio based plastics. This environmentally friendly approach can remove our dependency from fossil based conventional polymers and will lead us to a much more sustainable future.
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Introduction

One of the most grievous problems, that our planet is facing today is the upheaval generated by excessive and impetuous use of single use plastics. Plastics like polyethene, polyethylene terepthalate, polyethylene, polyvinyl chloride, polystyrene etc. are synthetic polymers that find immense applications in day to day life of mankind. Owing to their properties like stability, malleability and durability they are widely used in manufacturing commodities of commercial importance. The diversity of these polymers, versatility of their properties and the technological advances they have brought, has made them an indispensable part of human life.

Conventional plastics are derived from non-renewable fossil fuel like petroleum, and have been further modified to improve their properties. These modifications are achieved by an addition of various ingredients like flame retardants (to reduce combustibility) coupling agents (to enhance structural bonding), lubricants (to lower friction/viscosity of the molten plastic), plasticizers (to improve flexibility) and colorants (to impart color), to the naïve polymer resin.[1] These additives render the polymers with properties they are known for, but at the same time, make them responsible for the adverse effects on both the environment and human life. Most of these additives are used in substantial quantities and are potentially toxic (being resistant to degradation). These conventional polymers persist in the environment, leading to an accumulation in water and land resources and subsequent pollution.[1] The micro plastics which comprises of bits of plastics smaller than one-fifth of an inch, are readily ingested by biota and accumulates in the food chain. These pollutants have been shown to have detrimental effects on human health, including hormonal disturbances, developmental issues, cancer and immunocompromised conditions.[2] They also have adverse impacts on marine ecosystems, by causing death of birds and fishes by ingestion and choking. Though the consequences of plastic pollution on the environment are now widespread and noticeable, their long term impact on humans and wild life are yet to be investigated. The current methodologies for disposing these conventional plastics and strategies for recycling and reusing them are not effective.[3] In this scenario, the world needs to find a solution that may mitigate the disadvantages of conventional plastics, giving continued access to this miracle material at the same time.

Bio based plastics can be a promising alternative to the conventional petroleum based plastics and can be represented as an ecofriendly approach towards resolving this issue of great concern.

This study, gives an insight to plastics of biological origin and various biological wastes that can be utilized for the production of such plastics. The bio based plastics developed from biological waste are not only environmentally friendly, but can also pave the way for organic waste management, in a more effective manner. Extensive research and novel approaches towards these bios based plastic production would lead to an increased environmental sustainability and expectancy of human life. There are few hindrances towards the complete replacement of conventional plastics with bio based plastics, that includes higher capital cost and problems associated with disposal and recycling. However, with the growing environmental concerns and inclination towards sustainable development, there is increased interest for research and development for overcoming the hindrances and developing viable industrial processes for manufacturing bio based plastics.

Bio Based Plastics

Bio based plastics are polymers of biological origin. Unlike fossil based conventional plastics, bioplastics are derived from microbes or plant sources. They are derived from both biological and biodegradable material. Biodegradability is inherent property of any material that allows it to undergo degradation on exposure to microbes. The time required for decomposition relies on the type of material and environmental conditions.[4] All biodegradable plastics are not necessarily bio-based. Certain polymers like Polybutylene Adipate Terephthalate (PAT) and Polycaprolactone (PCL) are derived from fossil fuels and are still biodegradable. Similarly, all bio based materials are not necessarily biodegradable.[5] To generalize, bio based plastics are plastics which are either generated from natural polymers present in biotic system or chemically synthesized from polymers, derived from biotic system. In addition, they can decompose and degrade naturally when introduced in the environment.

Bioplastics are comparable to conventional plastics in terms of strength and stability and therefore can be used for applications similar to the later one. Enhanced production and application of the bio based plastics would reduce our dependency on conventional fuels and substantially decrease the environmental hazards related to it. Additional advantages associated with bioplastics include reduced energy cost, carbon footprint and greenhouse gas emission and reclamation of byproducts[6] (Table 1). There is renowned interest towards developing bio based plastics, utilizing waste generated from agricultural and food industry. This in turn would provide us with better alternatives for waste management.

Table1. Comparative Account of Conventional Plastic and Bioplastic

Properties	Chemical Based Conventional Plastic	Bioplastic
Origin	Hydrocarbon	Agricultural waste, Food waste, Biowaste from effluent, Paper waste, Feather quill
Main products	Polyethylene (PE), Polyvinyl chloride (PVC), Polyethylene terephthalate (PET), Polystyrene (PS), Polyurethane (PU)	Cellulose, starch, lipid, chitin, protein based bioplastics; Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA), Polyhydroxybutyrate (PHB) polymers
Annual production	311 million tonnes	4.2 million tonnes
Life cycle assessment	Fossil resources required	Made up of bio waste and based on renewable resources
Toxicity	Bisphenol A (BPA), a hormone disrupter that is often found in traditional plastics and also eco-toxic	Less toxic and does not contain bisphenol A (BPA)
Sustainability	Mainly non-biodegradable but biodegradable is also available	Mainly biodegradable but some are non-biodegradable
Production cost	Respectively low	Costly with respect to conventional plastic
Energy consumption	More energy uses during production	Less uses of energy respectively
Effect on environment	Increases global warming, leads to abiotic depletion, reduces soil fertility	Mostly eco-friendly, no harm to abiotic factors, increases soil fertility

Types of Bio Plastics

Bioplastics constitutes a broad family of materials having different origins, properties and applications. Any polymer is described as a bioplastic if it is either bio-based (obtained from microbes or renewable feedstock), or biodegradable (decompose naturally, under appropriate environmental conditions), or both. Thus bioplastics can be classified into three categories (Figure 1).

Fossil-based Biodegradable Plastics

These plastics are a group of materials,that are derived from petroleum and still have the ability to decompose naturally. Polyesters, such as polycaprolactone, polyglycolic acid, polybutylene adipate-co-terephthalate and polybutylene succinate belongs to this group. The ester linkage in the backbone of these polymers, renders them with the hydrolytic instability and biodegradability.[7].

Bio-based and Non-biodegradable

Well known commodity plastics like Polyvinyl chloride and Polyethene, derived from bioethanol fall under this category. They are chemically similar to their fossil based counterparts and are non-biodegradable. However, they do not release additional carbon dioxide during incineration, thus have lower carbon foot print. Bio-based polyamides, polyepoxides and polyesters (e.g. polytrimethylene terephthalate) also belong to this category.[8]

Bio-based and Biodegradable Plastic "The True Bioplastics"

These polymers are manufactured from renewable sources of biological origins. Most of the plastics belonging to this category are derived from natural polymers like proteins, polysaccharides, lipids of plants or from animal origins. Another group of such plastics are products of microorganisms for example poly hydroxybutyrate (PHB). In addition, these plastics can also be chemically synthesized from bio-derived products for example polylactic acid (PLA). Owing to their biological origin and biodegradability, they are the true representatives of bioplastics. These plastics are mixed with appropriate plascticizers to make them usable for commercial purposes. Different types of bio-based and biodegradable plastics are further described below.

Protein Based Bioplastic

Proteins are polymers of amino acids having indispensable biological functions in a living cell. Various proteins from animal and plant origins have been explored to produce bio based plastics. Proteins present in cocoa bean, soy, corn gluten, wheat, linseed meal and sorghum meal have been investigated to be used as bio plastics.[9] Similarly, egg albumin, fish proteins feather meal, cattle horn and leather scrap are the major sources of animal proteins studied for plastic production.[10] Most of these proteins are produced as industrial waste or by-products and are easily available at low cost. Although proteins are natural polymers, but, when compared to synthetic polymers, their structure is much more complex. In order to function like a synthetic polymer, the protein needs to be modified and extended to form a three-dimensional network.

This can be achieved by reducing the covalent and non-covalent interactions that stabilizes a protein, which leads to unfolding protein and forming new three dimensional structures, similar to the semi-crystalline synthetic plastics.[9] The processing conditions often depends upon structural properties of the protein being used as raw material, and it also determines mechanical properties of the final product.

Soy protein is one of the most extensively studied protein for bioplastics production. The thermo mechanical molding of soy protein plastics occurs at a temperature between 120 °C to 140 °C and its mechanical properties highly depends upon the moisture content of raw material. Actually the lesser the moisture, the brittle the plastic would be. The moisture content is regulated by drying and adding plasticizers such as glycerol.[11,12] Similarly, the egg-white proteins (a protein of animal origin), has been studied for producing plastics. It is heated to a temperature of 136.5 °C ± 3 °C, which leads to breaking hydrogen bonding and hydrophobic interactions of the protein, permitting it to take structure of bioplastic.[13] Several researchers have investigated the use of egg white protein for plastic production.[14,15] Another protein that has been widely studied for plastic production is the whey protein. Whey is the byproduct of dairy industry and has antimicrobial properties. Whey based plastics are widely used in the production of films and food packaging material.[16] Potential Potential applications of protein based plastics include home and garden supplies, toys and industrial

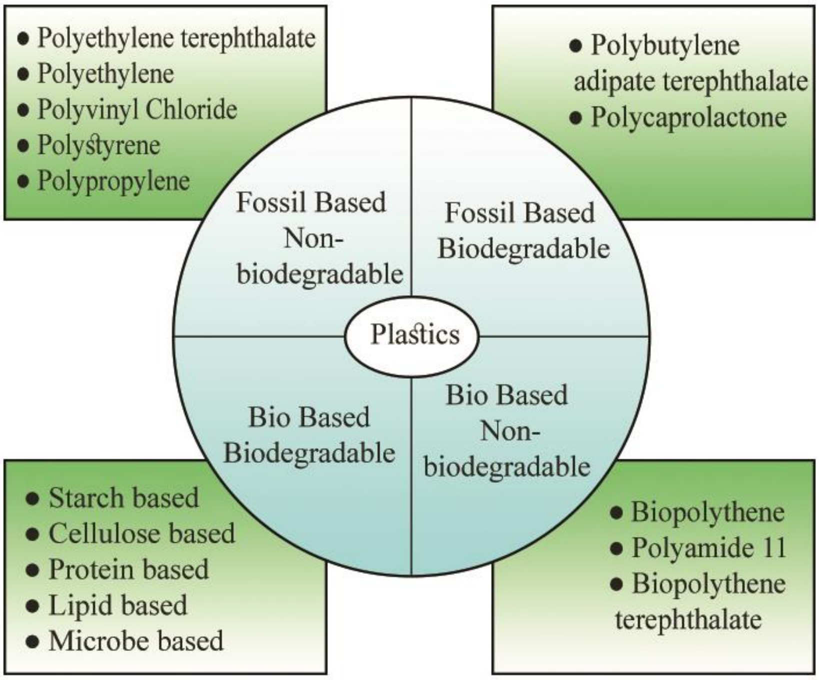

Figure 1. Types of Plastics, Their Degradability and Examples. Except the fossil based non-biodegradable plastic, rest three are considered under the category of bioplastics.

packaging. They are useful in producing dissolvable films in horticulture, medical cosmetic and textile industry and packaging films in the food industry.[15,17] Although protein-based plastics have globally drawn interest, but the challenges in the production and performance of these plastics, narrows down their applications and seeks extensive research in this field.

Lipid Based Bioplastic

Lipids are ester of fatty acid and it derivatives, having immense scope in commercial applications. A wide range of lipids derived from plants and animal sources can be used to develop lipid based bioplastics.

A wide range of lipids derived from plants and animal sources can be used to develop lipid based bioplastics. Different classes of polymers *viz.* polyester, polyurethanes and epoxy resins have been developed from plants and animal based lipids having properties comparable to their crude oil based counterparts.[18] Castor oil, olive oil, palm oil, linseed oil and soya bean oil have been investigated for the production of bioplastics.[19] Recent developments in the production of low cost microalgae derived oils have a great scope for growth in this area.[20] Triglyceride oil extracted from plants are found inside the seeds. The seeds are cleaned, dried and mechanically pressed to extract the oil in it.[21,22] After extraction, the oil is clarified and residual water is removed, which is followed by refining, degumming and bleaching to get a purified product. Purified oil is manipulated further by reactions like transesterification, ring opening epoxidation etc. to convert into plastic form.[23,24] Plant oil based polymers have been reported to have appreciable mechanical properties like improved thermo stability, better tensile strength and elongation, combined by inherent biodegradability.[25] Lipid based plastics can be used in manufacturing composite structure, paint formulations, foams, biomedical application (wound dressing and assisted drug release) and as packaging materials.[25-27]

Starch Based Bioplastic

Starch is used as a raw material for manufacturing in a wide range of industrial applications. Starch is the energy reserve in plants, and therefore is found in abundance. Starch imparts textural characteristics and has gelling or film formation ability, which makes it a valuable product for industrial applications. Starch is used in various industrial applications namely emulsifying agent, thickening agent, defoaming agents and as sizing agents.[28] The majority of the starch produced globally is derived from corn. In addition to cassava, wheat, rice, pea, tapioca, potato are other major sources of starch. It is generally extracted from plant sources by the wet milling method. Synthesis starts with the extraction of starch from plant sources, followed by the gelatinization and addition of plasticizers.[29,30]

In starch based plastics, starch may be used as native starch, modified starch or in form of blends with other synthetic polymers. Owing to their properties like thermoplasticity, flexibility, low cost, water repellant nature and biodegradability, starch based plastics find a wide range of applications. They are utilized to make sacks and packs, diaper films, air bubble films, pots, cups, and pharmaceutical bundling.[31,32] However, most starch-based polymers exhibit poor mechanical properties and poor moisture stability. Therefore, the current research is oriented towards improving these properties of starch based plastics, through starch modifications and addition of compatibilizers and reinforcements, so that they can be a viable alternative to conventional plastics.

Cellulose Based Bioplastic

Cellulose, as the main component of the cell wall of plants, is the most abundant organic compound found in nature. The cellulose content in plants may vary from 50% to 90%, depending on the type of plant. Cellulose derived from higher plants is present as a mixture of cellulose with hemicellulose, lignin, polysaccharides other than cellulose like pectin and hemicelluloses. For commercial applications, cellulose is mainly derived from wood pulp and cotton linters.[33] Cotton linters are the residual fibers present on cotton seeds, left after the long fibers are removed for textile industry. The cotton linters are digested and bleached to get purified cellulose.[34] On the other hand, cellulose is produced from higher woody plants via pulping process, which involves removal non cellulosic matter via chemical/enzymatic process, to obtain purified cellulose. The processed cellulose is treated with acids and anhydrides to obtain cellulose esters, that are used in the production of cellulose based plastics. The acetates, butyrate and propionates of celluloses are abundantly used in the production of plastics.[35,36] Among these cellulose acetate is a tough, clear, stable and flexible plastic with excellent resistance to organic and inorganic chemicals. Often, plasticizers are added to further improve its properties. Ether cellulose and cellulose nitrate (celluloid) are other forms of cellulose useful in plastic formation.[35,37]

Lignocellulosic biomass and the cellulose rich waste from the food industry are currently looked upon as cheap sources of cellulose for plastic production. Important applications of cellulose based plastics include plastic films for LCD and antifog goggles; cellulose based coatings for metal and wood, filters for window cartons, printing inks etc., and water-soluble films used for packaging medical capsules and detergent powders, that readily dissolve in water.[38]

Chitin Based Bioplastic

Chitin is an abundant mucopolysaccharide, present naturally as supporting material in exoskeleton of insects, crustaceans. It is known to consist of 2-acetamido-2-deoxy-β-D-glucose through a β (1 → 4) linkage. It is an inelastic, white, nitrogenous polysaccharide,[39] plays a good role in biotechnological field due to its biologically degradable, biocompatible and bioreactive nature.[40] The key sources of the raw materials for chitin production are the shells of crustaceans mainly shrimps and crabs. Chitin is found in crustacean shells, in form of complex network with proteins on which calcium carbonate is deposited.[41]

Chitin along with chitosan which is derivative of chitin recently looking for a cheaper source for producing plastic. Bioplastic based on chitosan, is biodegradable, biocompatible, molded into complex shapes easily and also cheaper as the wastage material of shrimp is widely available. The presence of microfibers in chitin suggests that it has characteristics for fiber spinning. Fibers, based on chitin as well as chitosan are useful as absorbable structures and also as wound dressing materials.[42] Chitin based plastics can be used in the production of cups, clips, egg cartoons and many other products.

Polyhydroxyalkanaote Based Bioplastic

Polyhydroxyalkanaote (PHA), are intracellular, carbon storage compounds produced by bacteria, as energy reserve to combat carbon limiting unfavorable conditions. Bacteria endures this environmental stress, by initiating a cascade of metabolic events that leads to PHA degradation.[43] The PHAs are synthesized by both gram-negative and gram-positive bacteria, which store them, within the cells in the form of granules and few bacteria can accumulate PHA as much as 90% of dry weight of cell. Polyhydroxyalkanoates are linear chain of polyester made up of hydroxy-acid as monomers, having carbon length ranging from C3 to C14. Owing to their properties like biodegradability, thermoplasticity and biocompatibility, PHAs has gained importance as an ecofriendly polymer for industrial applications.[44] Bacteria produces PHA as a secondary metabolite in carbon rich culture medium, which can be recovered by cell disruption, solubilization of impurities and centrifugation. The most common PHA, which is used in polymer production is Poly Hydroxybutyrate (PHB). The majority of PHA constitute two or more types of monomers, and are referred as heteropolymers, eg 3-Hydroxybutyrate and 3-Hydroxy Valerate. Depending on the type of the carbon source and microorganism provided during the growth, bacteria are capable of incorporating different hydroxylated monomers into PHA, giving a rise to different types of PHAs.[45]

Owing to feasible physical properties and extended performance, PHA and its derivatives are used in a wide range of end use industrial applications. Earlier applications of PHA were mostly limited to packaging but its importance in medical field has now become significant.[46] PHA can be used to make water-resistant surfaces of cardboards and papers, foils, films, diaphragms and articles of personal hygiene such as diapers.[47] The properties of biocompatibility and biodegradability of PHA, play a major role in its application in medical industry.[48] In a pure form or as composites, PHAs are used in different medical applications such as, sutures, skin substitutes, dressing, dusting powders in wound management, heart valves, vascular grafts in vascular system devices, scaffolds for cartilage engineering, screws and bone graft substitutes in orthopedic and regeneration of arterial tissues, and biomedical materials for drug delivery.[49-51] PHAs are also used in various applications in the field of agriculture, namely encapsulation of seeds and fertilizers, plastic films for crop protection, biodegradable carriers for herbicides and insecticides.[51]

Polylactic Acid Based Bioplastic

Polylactic Acid (PLA), a multipurpose biodegradable polymer, is derived from polymerization of lactic acid. The lactic acid monomers are obtained from fermentation of starch/sugar from renewable plant sources like corn and sugar cane. Sugar beet, tapioca and wheat are other examples of cheap renewable resources used for PLA production. For the production of PLA, starch/sugar is extracted from the raw material and subjected to fermentation using Lactic Acid Bacteria (LAB), that leads to the formation of lactic acid. The produced lactic acid is chemically treated and polymerized by methods like polycondensation reaction or ring opening polymerization or azeotropic dehydrative condensation, to make the final product. Ring opening polymerization leads to a high molecular weight product, which makes this method the most viable process to produce PLA.[52,53] However, few new methods such as polymerization using ultra sonic waves and microwave irradiation may lead to a cheaper and faster production of PLA.[54] The properties of PLA is quite comparable to other conventional polymers such as Polypropylene (PP), Polyethylene Terephthalate (PET), or Polyethylene (LDPE and HDPE) and is indeed biodegradable. The major advantages of the PLA plastics are their stability, rigidity, plasticity, transparency, and ability to blend with equipments and processes of existing fossil based plastics industry. PLA plastics find applications mainly in manufacture of containers, cups, tea bags, packaging films, bottles etc. The use of these plastics are extending to other various industries like medical, automobile, cosmetics and the textile industry.[55]

Bio Wastes for Production of bio Based Plastics

The majority of raw materials used for bio based plastic production comprises of starch and cellulose, derived from agricultural crops. Hence, a large scale of industrial productions of these plastics will require the utilization of cultivable land for producing the raw materials, which otherwise should have been used for producing food. This competition for agricultural land, obviously raises ethical concerns over expansion of bio plastic industry. In addition, the cost incurred in growing these crops and their subsequent processing, make the production of bioplastics a costly affair. These concerns can be addressed to a larger extent, by using biological or organic waste, as renewable sources of raw material for producing such plastics. Significant amounts of bio waste are generated from commercial activities and disposal of such waste is extremely challenging for manufacturers, specifically in the food and agricultural sector. In the current scenario, sustainability being a keyword, these industries need to develop strategies to reduce their environmental footprint. Hence, utilizing different types of bio wastes for manufacturing products of commercial interest can mitigate this problem to a greater extent (Table 2). An overview of various strategies for conversion of bio waste to bioplastics is shown in Figure 2. The waste generated from various industries, that may be utilized for producing bio based plastics are described below:

Lignocellulosic Agricultural Waste

Agricultural wastes are the byproducts of cultivation and processing of agricultural products like crops, vegetables and fruits. Enormous amounts of agricultural wastes are annually generated worldwide. Such large quantity of wastes from agricultural sources includes sugar cane baggasse, corn cob, corn husk, rice straw, wheat straw, wheat bran etc. In addition, every year about half of the produced fruit and vegetables are globally wasted due to reasons including pests, inefficient storage and during transportation. This huge quantity of waste can be efficiently managed and commercially utilized for the production of bio based plastics.

The agricultural residues are rich in lignocellulosic material which may serve as renewable sources of cellulose and have potential application as cost-effective raw material for plastic production. Moreover, it represents a sustainable strategy to combat environmental pollution associated with open biomass.[56-58] Rice straw is one of the important wastes in this regard. Around, 800 to 1,000 million tons of rice straw is annually produced worldwide. Rice straw is either burned in the field or dumped into water sources, which results into greenhouse gas emissions and pollution.[59] As rice straw is rich in cellulose (32-47%) it can be efficiently used for the production of cellulose based plastics.[60] In one the studies, researchers used rice straw as raw material for the production of PHB biopolymer, by *Pseudomonas aeruginosa* species.[61] They used various concentrations of microcrystalline cellulose extracted from rice straw as source of carbon for bacterial growth and production PHB plastics. Similarly, rice husk generated after processing rice, has also been evaluated for the production of plastics.[62,63]

Wheat bran is another abundant and less exploited agricultural residue that has the potential to be applied in the plastic industry. Rahman et al. used wheat bran for producing thermoplastic composites, having improved mechanical properties.[64] Van et al. have investigated the production of PHB by *Halomonas boliviensis* LC1 using wheat bran in the fermentation medium.[65] Other various agricultural wastes that has been utilized for plastic production includes corn cob,[66,67] corn husk[68,69] and sugar cane bagasse.[70] Thus, numerous studies have been carried out for utilizing lignocellulosic biomass for the production of polymers. However, a wide range of such wastes are yet to be investigated.

Food Industry Biomass Waste

Food processing wastes are rich in organic content and are degraded naturally under appropriate environmental conditions. However, when generated in significant quantities, they pose disposal and management related problems and ultimately lead to pollution. The organic matter present in the food industry waste can be used for generating various value added products, bio based plastics being one of them. The food industry biomass wastes that have been potentially utilized for the production of plastics are discussed below:

Table 2. Different types of biological wastes that have been used for production of bio based plastic

Types of Waste	Examples of Bio Waste	Type of Plastics Produced	References
Lignocellulosic biowaste	Sugarcane bagasse, cotton linters, corn cob, corn husk, rice husk, rice straw, wheat bran	Cellulose Based bioplastics and PHB polymers	[20, 61-63, 65, 67-70]
Food industry biomass waste	Peel waste: Cassava, potatoe, pineapple, orange and banana peels	Starch based bioplastics and Cellulose based bioplastics, PLA and PHB polymers	[73-79, 83-87]
	Seed waste: Mango, Date, Avocado, Jackfruit	Lipid based bioplastic, Starch based bioplastic, PHB polymers	[73, 88-91]
	Crustaceans shells waste: shells waste from squilla, shrimp, crab, lobster, prawn like crustaceans	Chitin based bioplastic and nanostructured film.	[93, 96]
	Waste oil: Waste frying oil, Non edible oil like Castor and Jatropha	Lipid based bioplastic, and PHA polymers	[101-107]
Biowaste from effluents	Domestic waste water, Food and dairy industry wastewater, Wood mill effluent, Oil industry effluent	PHB, PHA, poly-3-(hydroxybutyrate-co-hydroxyvalerate) and PHA polymers	[108-114, 116, 117,119,120]
Miscellaneous waste	Municipal solid waste Feather quill Paper waste	PHA, Protein based bioplastics, PLA polymers	[121-123, 126-130]

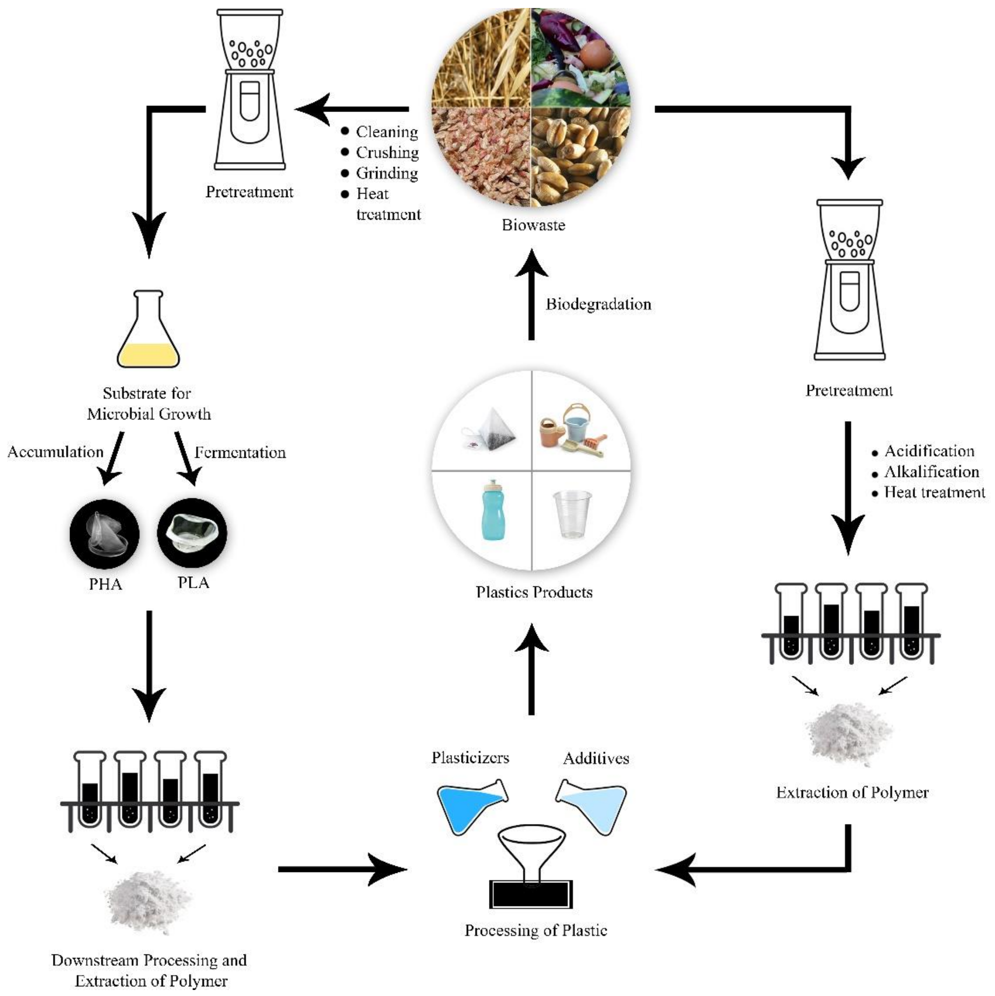

Figure 2. Generalized Process of Bioplastics Production from Biological Wastes.

Peel Waste

Peel waste includes the peel of different types of fruits and vegetables obtained from the food processing industry. Peel waste is mainly produced from juice producing industries and becomes a nuisance for the manufacturers and environment as an unmanageable solid waste.[71] Fruit and vegetable peels are rich sources of cellulose and starch that can be utilized for the production of bio based plastics. One of the important peels that has been studied for polymer production is the cassava peel. Approximately, 50 million tons of cassava peel is generated per year, which are either burnt or left in piles. The main constituents of cassava peel are protein, cellulose and hemicelluloses.[72] Cassava peels have been investigated for the production of starch based bioplastics, where in starch obtained from cassava peels was fortified with cellulose and sorbitol as plasticizer to yield good quality plastic.[73] Cassava peel based plastics have important application in food packaging as reported by Dasumiati et al.[74] Similarly, potato peel wastes have also been reported for plastic production. These peels are rich in starch, cellulose and hemicelluloses and are generated in large quantities by potato processing in industries. Bezirhan and Bilgen have reported the production of starch based plastic from potato peels and checked its biodegradability.[75] PHB and PLA production can also be done using potatoes peels in fermentation medium.[76,77] Pineapple peels have been investigated for the production of plastics based on cellulose[78] and PHA.[79] Around 60% (w/w) of the weight of pineapples is comprised of stem, peels and crown, which can be used as cheap sources of raw material for the production of plastics.[80,81] In addition to the above mentioned points, plastic production have also been reported from orange peels,[82,83] banana peels[84,85] and vegetable wastes.[86,87]

Seed Waste

Various types of seed waste are generated from the food processing industry, which ultimately leads to problems related with solid waste management. Seeds are generated as waste for e.g. mango seed, date seed, avocado seed etc. have the potential to be used as raw material for plastic production. The mango seed comprises of starch, fat and protein and is mainly discarded as waste. The oil of mango seed kernel is rich in unsaturated fat that can be used to produce lipid based plastics. Moreover, the high starch content can also be used for the production of starch based polymers.[73] Date seed also makes the major part of dates and is a rich source of carbohydrate and fat. In a study, the oil derived from date seeds was used to produce PHB polymer. In the same study, the mechanical, thermal and degradation properties of the plastic were also investigated.[88] Starch based bioplastics have been produced using avocado seeds as substrate. In a study, bioplastic was produced from avocado seed extract mixed with cellulose and ethylene glycol as plasticizer as previously mentioned.[89] Bioplastic production from avocado seed starch utilizing Schweizer's reagent as solvent has also been reported by Lubis et al.[90] In addition, jack fruit seeds have also been studied for starch based plastics using glycerol as plasticizer.[91] Thus there is a great scope in investigating various fruit seeds as sources of raw material for manufacturing ecofriendly polymers.

Bioplastic from Crustacean Shells

Another economical, eco-friendly bioplastic production procedure is from crustacean shells, a major waste product of food industries. Every year, some 6 to 8 million tons of waste lobster, shrimp and crab shells are produced worldwide.[92] The key structural component of the exoskeletons of crustaceans is a bio polymer named chitin. Squilla, shrimp, crab, lobster, prawn and fish scale waste are very good raw material for the production of chitin.[93] Through chemical or enzymatic deacetylation, chitin is transformed to its derivative, chitosan.[94,95] Extensive applications of chitin and its derivatives are already noticed in the medical field during the last three decades. Moreover, chitosan finds application in photography and cosmetics. Chitin and chitosan obtained from crustacean wastes have good potential to be used for bioplastic production.[39]

Chitin and its derivatives has been investigated by many researchers for the production of bioplastics. Hudson et al. prepared a chitin or chitosan homogeneous solution in 1 L of dilute acetic acid and white vinegar and poured it directly into the molds. At the temperature of 30-40 °C, they allowed the solvent to evaporate and developed reasonably durable and thick plastic pieces.[96] Fernandez and Ingber utilized chitosan to make large scale functional objects like clips, egg cartoons, cups and chess pieces.[97] Similarly Pandharipande and Bhagat also utilized the chitin synthesized from crab shells and prepared nanostructured film.[93]

Chitin can be blended with other polymers that can render better mechanical properties to the plastics. Shen et al. performed a research on bioplastic manufacturing from potato starch by adding chitosan. They added chitosan to the potato starch at 5%, 10%, and 15% by the weight of starch and reported that, 15% had a better mechanical strength.[98] Chitosan addition basically affects water absorption potential of bioplastics where the water absorption of bioplastics will reduce with increasing the concentration of chitosan. With the addition of chitin, the density of crystalline bioplastic is enhanced and thereby increases the water repulsion ability.[99]

Waste Oil

Waste oil, is any oil that is unsuitable for its intended purpose, due to either contamination or loss of its properties. Every year, millions of tons of waste oil is generated worldwide. Edible oil is mainly produced by the transesterification of oils obtained from plant sources. Several plant species like rapeseed, sunflower seed, olive, palm, soybean, and peanut are used to produce edible cooking oil. The extraction process involved in oil production generates wastes as residues in large amounts and poses disposal problems all over the world. The waste biomass generated after pressing and processing of oil is rich in cellulose and can be utilized for the production of plastics.[100] In addition, waste frying oil generated from households and food industries also poses disposal related threats. These wastes are rich in triglycerides and can be harnessed for the production of commercially valuable products including plastics. Rus et al. have investigated mixing polyurethane produced from waste cooking oil with the standard LDPE and HDPE. As a result, the produced plastic was much better than the native LDPA and HDPE in terms of mechanical properties and biodegradability.[101] The production of polyurethane from waste cooking oil has also been reported by Firdaus.[81] Waste frying oil is one of the best carbon sources for PHA based on polymers. The production of PHA using *pseudomonas putida* Sd12 which has tendency to utilize waste frying corn oil, has been done by Gatea et al.[102] Similar studies have also been reported by Song et al. (2008)[103] and Albuquerque and Malafaia.[104] The current research has also focused on investigating oil plants that produce non-edible oils as the renewable feedstock for plastic production. These plants can be grown on non-cultivable land, denying the possibilities of competition with crops for land. Cangemil et al. reported the studies of biodegradation ability of polyurethane derived from castor oil and its applicability for the replacement of conventional polyurethane foams.[105] Similarly, Kumar has reported the potential application of jatropha oil as a source of carbon source for producing PHA.[106] Thus, research oriented towards conversion of byproducts and non-food materials into plastics is gaining a lot of significance and is an exciting field of research.

Biowaste from Effluents

Waste water, is the contaminated water released from domestic, agricultural or industrial, activities. The wastewater contains complex organic compounds with high amounts of soluble solids which increases the biological oxygen demand of water and poses risk to the health of both the environment and human beings. The organic content in waste water can be utilized for plastic production, particularly PHB and PLA plastics as discussed below:

Domestic Wastewater

Domestic wastewater has high amounts of organic compounds that increases its biological oxygen demand and places it in the category of pollutants. It contains various organic constituents *viz* different types of carbohydrates, lignin, fats, proteins etc.[107] that can be utilized in bio polymer production. Ceyhan et al. have reported the production of PHB from *Enterobacter aerogenes* sps. using domestic wastewater in fermentation medium. The bacteria efficientlyused the organic content of wastewater and was able to accumulate PHB up to 90% of the dry cell weight thus reducing the cost of production by up to 50%.[108]

Food and Dairy Industry Wastewater

Milk whey is one of the byproduct from dairy wastewater treatment plant. Many researchers have shown its application in fermentation medium for production of PHA plastics.[109,110] In addition, effluent generated from starch processing industry, tomato cannery and sugar industry has also been investigated by many researchers for the production of PHA plastics.[111-114] In similar studies, vinasse which is a liquid by product of the sugar industry and is very rich in organic content has been investigated for the production of poly-3-(hydroxybutyrate-co-hydroxyvalerate) polymers using *Haloferax mediterranei* sps.[115] Oil mill effluent represents an abundant waste, rich in carbohydrates and lipids. The management of this waste has been puzzling oil producers for years. Many researchers have attempted to utilize it as a renewable feedstock for the production of plastics. Ntaikou et al. have investigated the use of olive oil mill waste water for biosynthesis of PHA.[116] Similar studies have also been reported with palm oil mill waste.[117,118] The organic matter present in effluents of various food processing industries can be considered as an extremely cheap raw material for producing commercial polymers.

Wood Mill Effluent

Wood plant effluents can be reasonable feedstock for the production of bio based plastics as they have high biological oxygen demand and can be used as feedstock for the production of PHA based plastics. For example, in a study by Ben et al. wood mill effluent was first converted to volatile fatty acids and was then used as substrate for PHA production using bacterial cultures.[119]

Miscellaneous Waste

Municipal Solid Waste

The organic part of municipal solid waste is mostly comprised of biodegradable materials which includes sugars, cellulose, hemicellulose, starch and protein.[120] This kind of waste has an incredible source of renewable feedstock for plastic manufacturing. Girotto et al. performed acidogenic fermentation of municipal waste to obtain precursors of polymer production like acetate, propionate etc.[121] Korkakaki et al. showed the production of PHA plastics from municipal solid waste.[122]

Feather Quill and Paper Waste

Feathers contain about 90% protein which is mainly keratin.[123,124] Many researchers have investigated the use of feather quills for protein based plastic production. Ullah et al. used sodium sulphide to extrude the quills and produced plastic from it. They also studied the effect of different plasticizers (propylene glycol, glycerol, ethylene glycol, and diethyl tartrate) on the mechanical properties of the polymer and showed that ethylene glycol interacted more effectively with quill keratin, exhibiting better transparency and mechanical properties than other plasticizers.[125] The keratin particles were also used to develop a bioplastic film, with microcrystalline cellulose as an additive.[13]

Paper waste is rich in cellulosic materials and can be efficiently reused asbiopolymers particularily poly lactic acid plastics.[126] Kapoor et al. and Singh et al. have reported the production of PLA based plastics from waste paper pulp.[127,128]

Future Trends and Challenges

Bioplastic has been emerged as one of the most innovative and ecofriendly materials developed in the past few years. Though bio plastics are gaining renowned attention as a promising replacement of chemical based conventional plastics, there are some hindrances that needs to be addressed in this regard. This mainly includes improvement in mechanical properties such as heat-resistance, and shock-resistance and processability, advancements in manufacturing technologies, expansion of applicability, establishment of standards and reduction in the cost of production. Current research in this field is focused towards resolving these issues. The mechanical properties can be improved by investigating better plasticizers and developing composite polymers rather than sticking to a particular type of polymer. This would help to expand the application of these plastics in different sectors. In addition, a wide range of biological sources specifically waste products, needs to be screened for making the process cost effective. These efforts would lead to rapid expansion in the bio plastic industry

Conclusion

Developing novel biodegradable polymers from renewable natural resources is gaining attention worldwide. This increased interest is primarily due to the adverse impact of non-degradable conventional plastics accumulating in the environment. The excessive and uncontrolled usage of conventional plastics and their environmental impact has necessitated the implementation of strategies for sustainable development. This can be achieved by switching to bio based plastics – plastics that is produced from renewable resources and are susceptible for biodegradation. Bioplastics are either derived from natural polymers *viz.* protein, starch, lipid and cellulose or by using microbes. Although they are environmentally friendly, but the process of production is complex which reduces its economic feasibility. This problem can be resolved to a greater extent by using organic wastes of biological origin, as raw material for the production of bioplastics. Huge amounts of waste are annually generated from different industries which can be effectively utilized for this purpose. This strategy can also help in organic waste management. The bioplastic market is rapidly developing and as a result globally known brands are investing in this sector. Further growth is expected with extensive research which would mitigate the problems associated with the current technology of bio plastic production and completely remove our dependency from fossil based conventional polymers.

Authors' Contributions

NG presented the idea for the article and critically revised the work. AD performed the literature search, analysis and drafting. SS and SB performed the literature search and drafting.

Conflict of Interest Disclosures

The authors declare that they have no conflicts interest.

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