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ARTICLE

Degradable biopolymers from agro and food waste: potentials and challenges

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ABSTRACT

The synthesis of biodegradable plastics from diverse biological resources has garnered significant attention in recent years. The escalating demand for petroleum-based plastics in daily life presents a growing concern due to their non-degradability and production involving hazardous chemicals. The disposal of solid waste is a pressing issue, particularly in densely populated countries like India. Biodegradable waste generated from various sectors, including agriculture, industries, and households, significantly contributes to environmental challenges. Effectively managing such waste remains a formidable challenge. Given the profound environmental impact, there is an imperative need to prioritize waste management across various sectors. Notably, biologically treated waste streams have been found to contain a rich reservoir of organic materials, which can serve as valuable feedstock for the synthesis of biodegradable plastics. Biodegradable plastics, derived from renewable biomass sources, offer an eco-friendly alternative to conventional plastics. The synthesis of biodegradable plastics from a variety of biomaterials represents the present and future frontier in mitigating environmental threats posed by commercial plastics and the accumulation of waste in landfills. This review offers comprehensive insights into the significance of bio-based plastics derived from a range of biological waste resources and their multifaceted applications across diverse fields, emphasizing their pivotal role in achieving a more sustainable and environmentally responsible future.

1. Introduction

Plastics have become a significant material in day-to-day life by finding their applications in various products (Chidambarampadmavathy *et al*., 2017). The increasing usage of plastics leads to various environmental and health hazards due to their persistence and non-biodegradability (Huang *et al*., 2022).Also these plastics get accumulated in both aquatic and terrestrial environments thereby polluting the nature (Ukaogo *et al*., 2020). The synthesis and incineration of plastic also generates numerous toxic chemicals which affect the environment (Choi *et al*., 2022).The bio-based polymers are considered to be an actual substitute for conventional polymers since they can degrade easily by reducing the environmental footprint associated with anthropogenic activities (Medeiros *et al*., 2020). The numerous environmental, financial, and health issues caused by conventional plastics have inspired several researchers to create biodegradable plastics, also known as bioplastics, which have proven to be safer alternatives to toxic petroleum-based plastics (Richard *et al*., 2009; Shafqat *et al*., 2020).

Natural organic substances including polysaccharides, proteins, and lipids are used to make bioplastics, and they can also be used as the starting point for the synthesis of bio-based polymers. (Reichert *et al*.,2020). Starch, chitin, lignin and cellulose are common polysaccharides used for the synthesis of bioplastics while gelatin, casein and gluten, and plant oils and animal fats are natural proteins and lipids respectively(Song *et al*.,2009). Bio-based plastics are polymers that can be degraded by the microbial action in a short period of time, under appropriate environmental conditions(Khare & Deshmukh., 2016).The commercially available biodegradable plastics are polyhydroxyalkanoates (PHAs), polylactic acid (PLAs),polyhydroxybutyrate (PHB), and polyglycolide (PGA) (Albuquerque & Malafaia,2018).Currently, biodegradable plastics are considered to be of greater importance in the material world and the demand for their usage will be evolved in the fore coming years (Stevens, 2002; Van et al.,2018;Vinod *et al.*,2020). The main barriers to the success of bioplastic are PLA's characteristics, which include thermal instability, difficult heat saleability, brittleness, low melt strength, high watervapour content, and oxygen permeability. These characteristics can be changed in the near future by additional research studies (Jabeen *et al*., 2015).

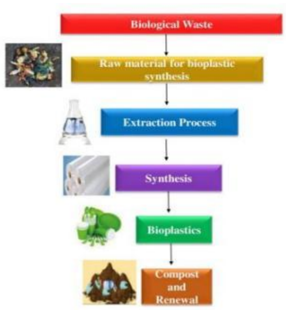

Figure 1: The Synthesis of Biodegradable Plastic from Biological Wastes.

Bioplastic finds its application and advantage not only in biodegradability but also it shows its importance in reusing/recycling waste in their synthesis (Figure 1). Bioplastics are able to biodegrade more readily than fossil fuels derived plastics. The structure and composition of bioplastics also have an impact on the biodegradation process and thereby reduce greenhouse gases emission (Kale *et al*., 2007).

2. Biodegradable plastics from various biological waste resources

It was estimated that globally, 1.3 billion tonnes of solid waste (mainly consists of biological waste) were produced every year (Daniel & Perinaz., 2012). By 2025, it was predicted that these wastes may increase to 2.2 billion tonnes and in low-income countries, the disposal rate may double in next 20 years (Oxford Analytica Daily Brief, 2018). The cost of management of these wastes may increase from $205.4 billion to $375.5 billion in the next 5 years, this may affect the low-income and lower middle-income countries (Srivastava & Chakma., 2022). Thus, waste management has become a challenge for the government of many developing countries. Therefore, it is important to notice while managing these wastes it should be economically minimal and environmentally sound (Abdel-Shafy & Mansour., 2018) (Fig. 2). Hence, a circular economy approach can be designed in the form of recycling the wastes to products like biofuel, biofertilizers, bioplastics, etc. (Table 1) (Fig 3). Thus, in this review, a circular economic approach for synthesizing biodegradable plastics from various biological waste resources such as domestic and commercial waste, industrial organic waste, agricultural waste, marine waste, etc.have been discussed.

2.1 Banana Peel

Banana peel is a common biological waste effectively produced from domestic and industrial waste. Banana peel is found to have an abundant supply of starch and other organic materials and also, they are a cost-effective source possessing various environmental-friendly properties. The common types of bioplastics are based on cellulose, starch, PHB, PLA. (Chodijah, S., *et al*., 2019) Starch is considered to be one of the most common sources of bioplastic production. Banana serves as a promising raw material for the production of bioplastics since the amount of starch present is comparatively high in the banana peel. Starch behaves as a thermoplastic in the presence of a plasticiser and hence a massive amount of plastic can be generated from the unused peels of banana which represent about 30%-40% of the fruit mass (Riya & Arivoli, 2019). Thus, through the data collected from the tests that have been done on the prototype, it was concluded that the bioplastics made from the banana peel can be used for industrial uses.

2.2 Coconut Husk

The management of Coconut husk requires instantaneous attention since, only the edible portions of the coconut fruit are consumed, whereas, the remaining parts like husks are thrown away or burnt. Hence handling the coco nut husk waste has become more of an environmental trouble. Generally, the coconut fibres are highly beneficial due to their properties. The coconut fibres can be divided into two categories: white fibres that are derived from immature coconuts and brown fibres that are extracted from mature coconuts. Brown fibres are thick, strong and have high abrasion resistance,

Table 1: The Advantages, Disadvantages and Applications of Various Biological Wastes.

S. No	RAW MATERIAL	ADVANTAGES	DISADVANTAGES	APPLICATION	REFERENCES
1	Banana peel	. Environment friendly . Starch content is comparatively high	Expensive production process	. Biodegradable bags . Intravenous Tubes	Chodijah et al. 2019; Riya & Arivoli, 2019; Huzaisham & Marsi, 2020; Kiran et al., 2022
2	Coconut husk	. High abrasion resistance . Provide excellent insulation against heat and sound	The production process is complex	Multipurpose coir pith	Babalola et al., 2019; Memon et al., 2019; Akshay et al., 2022; Leow et al., 2022
3	Cassava peel	. Safe for consumption . Contains minerals such as calcium in the form of calcium oxide and iron in the form of ferric oxide	. Poor mechanical properties . Cannot withstand more than 100℃	. Packaging industry . Pack sausages for direct consumption	Kale et al., 2007; Maulida et al., 2016; Dasumiati et al., 2019; Tafa & Engida, 2022
4	Jackfruit	. Rich in starch and amylose . Have unique properties like low lipid content, acidity resistance . Possess high gelatinization temperature	Plasticizer is required to increase the plasticity	. Food packaging industry . Edible food plates	Lubis et al., 2017; Renata et al., 2018; Sarebanha & Farhan, 2018; Akshaya & Pavithra, 2019; Maysarah S, 2020;
5	Potato peel	. Low cost . Least degradation period (28 days)	. Poor mechanical properties	Packaging industry	Nuramidah et al., 2018; Ezgi et al. 2019; Ramesh et al., 2021
6	Fruit peel	Abundant source from many food industries	Difficult to process	Packaging industry	Shalini et al., 2010; Nur et al., 2018; Veronika., 2019; Listyarini et al., 2020; Yaradoddi et al., 2022
7	Tomato peel	Available in large scale and easily accessible	Excess water content may make the biodegradable plastic less efficient	Remove toxic metal ions; Removes pollutants from water	José et al., 2018; Chrysanthos., 2020;
8	Corn waste	. High quantity of cellulose and lignin . Improved mechanical strength, tensile strength and flexural strength	. Poor barrier property	. Food packaging . Edible packaging film . Fiber for textiles	Zhangfeng et al., 2017; Ting et al., 2020;
9	Rice Straw	. Increased compliance and ductility . High mechanical performance	Expensive chemical purification process	. Biodegradable cutlery, crafty items, tableware . Food packaging	Melissa et al., 2014; Fabjola et al., 2018; Le et al., 2019; Sain & Mukul., 2020

		. Easy accessibility . Decomposed in 105 days			
10	Food waste	. Good mechanical properties . Abundant source of raw material	Higher energy input is required	Value added products	Yu et al., 1998; Li et al., 2017; Yiu et al., 2019; Maragkaki et al., 2020; Sharma et al., 2020
11	Egg shells	. Rich in minerals . Good mechanical and biodegradability properties	. During extraction process bad odor is produced . Less effective	. Absorbent for heavy metals from wastewater . Industrial application . Biomedical implant materials	Fabio et al., 2007; Norhafezah and Muhammad, 2018; Marium et al., 2020
12	Nut shells	Very low moisture content Rich source of nitrogen, phosphorus and potassium	Slow degradation process	. Bioactive films . Food packaging films	Krishnan & Padmanabhan, 2020; Maria et al., 2012; Troiano et al., 2018; Larruama et al., 2021
13	Sugarcane bagasse and molasses	. Low cost carbon source for commercial synthesis . Large scale PHA production . Good electrochemical stability	Less efficiency	Biodegradable plates Packaging material Edible films	Abhishek et al., 2012; Naheed & Jamil, 2014; Suresh et al., 2020; Satita et al., 2020; Siti et al., 2020
14	Waste Glycerol Derived from Industries	. Renewable and cost-effective source from industries . PHA derived from waste glycerol resembles petroleum plastics . Easy to degrade	Process could be expensive	Fibers for textiles Medical implant materials	Chengjun et al., 2013; Ana et al., 2015; Kumar et al., 2015; Abidin et al., 2021
15	Papermill Waste	Eco-friendly and cost-effective production of PHB	The inorganic precipitation (calcium carbonate) occurs during the process can deteriorate the accuracy of sensor	Packaging material	Yang et al., 2012; Huda et al., 2019
16	Keratin	Good mechanical and thermal properties	Less tensile strength	Could be used in food packaging industries, biomedical implant materials, pharmaceutical industries	Liu et al., 2018; Navina et al., 2018; Tamrat et al., 2018; Alashwal et al., 2020

17	Sheep wool	. Good transparency . UV barrier properties . Thermal and mechanical stability	Source of raw material is limited	. Might find applications in regenerative medicine, . Coatings or packaging . Eco-friendly bags	Jeanette et al., 2009; Borja, 2019; Pawlak, 2020
18	Seaweed	. Green production method . Good physical and mechanical properties . More resistant to microwave radiation	Tensile strength need to be improved	. Edible cups, wrapper . Food and non-food packaging materials	Rajendran et al., 2012; Lim et al., 2021; Supratim et al., 2019; Sudhakar et al., 2021;
19	Fish Waste	. Good physical, chemical and mechanical properties . Easily biodegradable	Less stretchable	Biodegradable film in agricultural field and food packaging	Araújoa et al., 2018; Eleda et al., 2019; Siti et al., 2020; Surya Parthasarathy et.al., 2022
20	Shells of Marine Species	Good texture and transparency	. Long duration for extraction process . Low tensile strength	. Industrial, medical and pharmaceutical applications . Biodegradable containers	Pal et al., 2014; Hudson et al., 2015; Lorenz et al., 2016; Pandharipande et al., 2016; Thammahiwes et al., 2018; Divya & Daniel, 2021

Figure 2: The Effect of Biological Waste with and without Recycling.

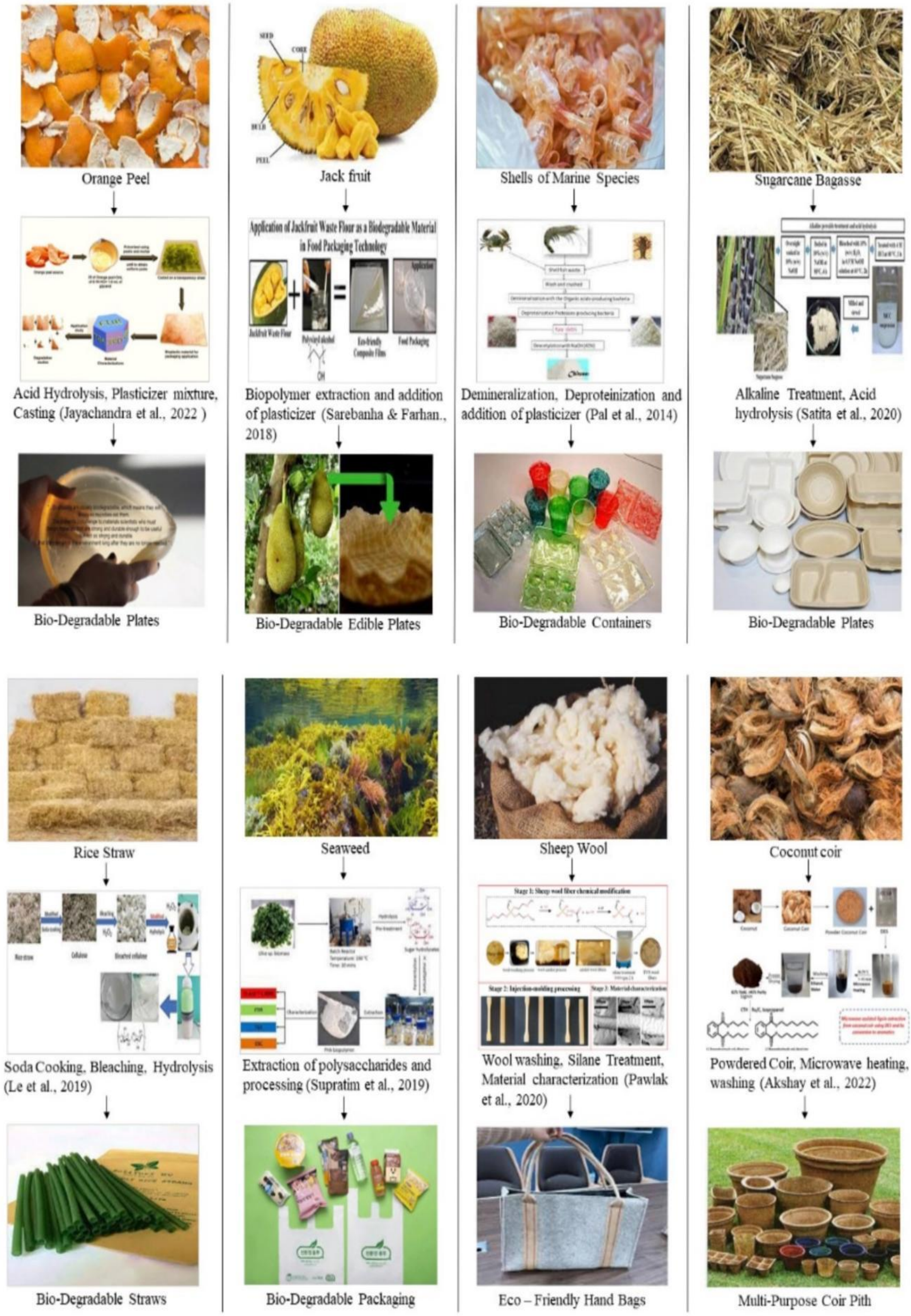

Figure 3: Utilization of Bio wastes.

provide excellent insulation against heat and sound, also unaffected by moisture and dampness whereas, white fibres are smoother and finer but weaker. From these properties, it is noticed that the conversion of coconut husk fibres into bioplastic is possible. From a study, it is observed that as the concentration of coconut fibre increases the tensile strength of bioplastic increases. Hence it is suggested that coconut husk which is thrown as waste can be utilized in the synthesis of bioplastic (Babalola *et al*., 2019).

2.3 Cassava Peel (Manihot uttilisima)

The food industries which deal with cassava processing results in the organic waste in the form of cassava peel.These cassava peels were found to have high starch content that can serve as a source for bioplastics synthesis (Maulida *et al*., 2016). However, starch-based bioplastic has many drawbacks, including poor mechanical qualities and significant moisture absorption, whereas the starch-based bioplastic material has high levels of protein and carbs. This implies that the produced bioplastic is legitimately deserving of use as a plastic wrapping for goods as well as for direct consumption, like sausages.

Multiple processes are utilized to create a bioplastic that can be easily removed from the mold and used to make plastic bags and packaging for food intended for direct consumption. By enhancing their characteristics with the biodegradable reinforcing filler, higher-value bioplastics can be produced. The production of bioplastics has physical and mechanical characteristics that are significantly influenced by the reinforcement fillers used.

The nature and thermal stability of bioplastic components obtained from cassava skin were determined by TGA (Thermogravimetric analysis). Food safety test estimated that the bioplastic material from cassava peel is safe for consumption and also contains minerals such as calcium in the form of calcium oxide and iron in the form of ferric oxide which can be considered as an additional nutrient while consuming bioplastic made from cassava peel (Dasumiati *et al*., 2019).

2.4 Jackfruit

Jackfruit tree (Artocarpus heterophyllus), a species that belongs to the Moraceae family and they found in many tropical and subtropical regions (Renata *et al*., 2018). The jackfruit consists of rind, edible yellow flesh, procarp, and seeds. It was found that the jackfruit seeds are rich in starch and protein and there are about 500 seeds that can be found in a single fruit, in which the seeds approximately weigh about 15% of the total weight of the fruit (Maysarah *et al*., 2020). It was also found that jackfruit seeds have some unique properties like low lipid content, acidity resistance, low pulp breakage compared to cassava and potato starch apart from it they were also rich in amylose and possess a high gelatinization temperature. Hence the jackfruit seed can be used as a raw material for the synthesis of bioplastic (Lubis *et al*., 2017). However, the use of plasticizers is necessary since they are challenging to integrate into the traditional processes of package creation and also, they aid in enhancing the flexibility of the bioplastic. Glycerol serves as an excellent plasticiser as they reduce the internal hydrogen bond that will enhance the intermolecular distance. Therefore, jackfruit seeds can serve as an ideal raw material for the synthesis of starch-based bioplastics.

2.5 Potato Peel Starch

As aforementioned, starch is one of the common biodegradable natural polymers and produced in abundance at low cost which can act as a suitable material for the fabrication of bioplastics (Nuramidah *et al*., 2018). Potato peel, a major source of starch is discarded by most of the food industries and thereby used in the bioplastic synthesis. It was found that the bioplastic from potato peel had a higher water absorption capacity than commercial bioplastic which can change the dimensions and mechanical strength of the bioplastic. It was also found that the biodegradability period of bioplastic produced from potato peel has the least duration (28 days) when compared with other bioplastics (Ezgi *et al*., 2019).

Potato starch can be used in a more specific application since it contains less amylose and amylopectin and more bound phosphorous. As a result, potato peel bioplastic is being used in the packaging industry as a viable substitute for petroleum plastic and has the potential to become a profitable product because it is made from renewable resources and can help to reduce environmental pollution. The higher water absorption and mechanical properties of bioplastic obtained from potato peel cause variation in dimensions of plastic which has to be rectified for frequent usage of this bioplastic in the food industry.

2.6 Fruit Peel

It is being reported that annually about 70 million tonnes of oranges are produced worldwide which is reported by FAO and nearly 40-60% of oranges are utilized for juice production on a commercial scale (Veronika.,2019).Likewise, many other fruits like apples, mangoes, grapes, etc. are used by numerous food industries all over the world (Yaradoddi *et al*.,2022). These industries almost generate 50-60% of waste after juice pressing which mainly contains peels, pulp, seeds, and membrane residues. These residues contain many useful biomolecules including polysaccharides, such as pectin, hemicelluloses,and cellulose, dind mono saccharides, minerals, etc (Listyarini *et al*., 2020). When these residual wastes were not treated properly, they can cause damage to the environment due to their high content of organic matter, water, and low pH. Pectin is one of the interesting materials for its ability to form a gel which will help in the synthesis of bioplastics. However, the majority of pectin can be extracted from orange waste (85.5%) and apple pomace (14%) worldwide (Shalini *et al*., 2010). Hence by processing pectin obtained from these fruit waste can produce bioplastics which will reduce the depletion of natural resources as well as minimizing risks caused due to waste disposal.

2.7 Tomato Peel

Tomato fruit is the second-largest primary vegetable crop in the world. Also, tomato is one of the crops getting damaged at the earliest and hence the quantity of tomatoes supplied to the vendors is equal to the quantity of tomatoes disposed as waste. Lycopene, a strong natural antioxidant present in the tomato has been highly utilized in the food, pharmaceutical and cosmetic industries for its biological properties (José *et al.*, 2018). But from these industries, the surplus things are generally burnt or dumped as waste, which in turn increases land and air pollution. Tomato skin, on the other hand, contains a polymer called cutin that is non-toxic, biodegradable, UV-blocking, amorphous, insoluble, and infusible. From the properties of cutin, various interior coatings of food cans are proposed with cutin-based material as a non-toxic and sustainable alternative to bisphenol A (BPA) resins. Also, tomato pomace contains various chemical components from which biopolymers extraction is possible (Chrysanthos., 2020).

2.8 Corn Waste

A whole corn/maize consists of outer husk, corn silks, grains/kernels and corn cob. As it is noted the corn kernel is one of the high fibre rich content food crop and the other parts of the corn plant are involved in processing corn oil which is further processed to produced corn starch or corn syrup, and protein feed. However, managing the corn waste which has been disposed frequently, since corn is one of the most produced food crops in the world after sugarcane, considered to be important by the environmentalists. The corn waste found to have chief content of cellulose, hemicellulose and lignin (Ting *et al*., 2020). Hence, researchers have identified improved bioplastic composites from these lignocellulosic fibers of corn waste. They also observed improved mechanical strength, tensile strength and flexural strength of the bioplastics obtained from corn waste since they contain a high quantity of cellulose and lignin. The application of this bioplastic in different sectors will be enhanced in near future (Zhangfeng *et al*., 2017).

2.9 Rice Straw

Rice straw is one of the most abundant agricultural residues found globally and it is also rich in cellulose, hemicellulose and lignin (Sain & Mukul., 2020). Since rice is the third-most-produced grain crop, there was a significant amount of crop waste, such as straw and husk. It is possible to estimate a global rice straw production of approximately 1000 million tons per year which can be utilized to produce a new biomaterial (Fabjola *et al*., 2018). In the untreated rice straw, cellulose fibers are embedded in hemicelluloses and lignin (Melissa et al., 2014). Regenerating cellulose from its derivatives takes more time and requires an expensive chemical purification process. Trifluoroacetic acid (TFA) reacts with the cellulose in rice straw after extraction and pretreatment to create cellulose-based bioplastic products. TFA is a volatile organic acid that has shown promise as a non-aqueous solvent for cellulose swelling.

The cellulose-based bioplastic may be cast in both wet and dry states; when cast in a wet condition, it has properties more akin to plasticized polyvinyl chloride than polystyrene in terms of mechanical behaviour. Water absorption is meant to be one of the notable properties of the bioplastic produced from rice straw. Since rice straw doesn't need to be separated from other waste, it may also be handled with ease. As a result, it seems feasible to create bioplastic from rice straw.

2.10 Food Waste

Food waste is being generated from all stages of the food supply chain. Food waste is often classified as industrial, agricultural, and household food waste (Li *et al*., 2017). Food waste from the economic sector and agricultural sector contributes a great deal of waste resources. Among all, major food waste is originated from the food manufacturing sectors. Generally, around 30 wt% food becomes as food waste and many food wastes are being generated all around the world, but just some of them only are employed for anaerobic digestion and composting and the remaining waste creating major land pollution. It is usually required for the conversion of food waste into value-added chemicals to end-use of garbage for increasing global sustainability (Yu *et al*., 1998). During the conversion process starch, cellulose, oils, other biomaterials of plants, livestock present in the food waste will interact with each other for energy transfer through physical/chemical/biological ways hence the amalgamation of bioplastics is possible with the properties of food waste. (Sharma *et al*., 2020) The production of bioplastics from food waste may be a renewable sustainable process, also it may be a perfect strategy for food waste disposal in the landfills which yields undesirable results, like greenhouse emissions and groundwater contamination (Yiu *et al*., 2019).

2.11 Egg Shell

Eggs are one of the major ingredients in a large variety of food product industries, bakeries, etc. whose production results in the disposal of tons of egg shells as waste. Annually 250,000 tons of egg shell waste is being produced worldwide (Fabio *et al*., 2007). The egg shell consists of ceramic materials forming a three-layered structure comprising the outer surface (cuticle), spongy layer (calcareous layer) and inner laminar layer (mammillary layer). Egg shells comprise of calcium carbonate (94%), calcium phosphate (1%), magnesium carbonate (1%) and other organic substances (4%). So, the egg shell is an abundant source of mineral salts, especially calcium carbonate. Also, the outer surface of the shell is enveloped with mucin protein which acts as a soluble plug in the egg shell. From these characteristics, the egg shells can be converted as beneficial material to the environment when it has been utilized appropriately. Hence, they can be used in the production of biodegradable plastics and the addition of eggshell as reinforcement material for the synthesis of bioplastic can be applied to improve the strength and stability of bioplastics and with rapid degradation process (Norhafezah and Muhammad, 2018).

2.12 Nut Shells

The shells or husks of various nuts (walnut, cashew nut, peanut, pistachio, etc.) from industries were discarded as waste. These shell wastes have already been used in different sectors like feedstock, personal care, laminating resins, etc. Currently, the production of bioplastics from these shells has been received considerable attention among researchers (Maria *et al.*, 2012). The biological components present in these shells made the process of bioplastic synthesis feasible since they contain starch, cellulose, lignin which are the important raw materials in the bioplastic synthesis (Troiano *et al.*,2018). Many innovations have been observed in the synthesis of bioplastic from nut shells in the current era which will provide the discovery of many novel bioplastics to replace the existing chemical polymers and thereby reduce environmental pollution.

2.13 Molasses

Sugar cane molasses, a rich source of carbohydrate dumped as waste by many of the industries which contain about 45% of sucrose (Suresh S *et al.*, 2020). The crucial component for the manufacturing of bioplastics utilising molasses was discovered to be the cane molasses, which produced the highest PHA by the soil bacterium Pseudomonas aeruginosa (Abhishek *et al.*, 2012). Over other inorganic nitrogen sources, urea played a featuring role in the manufacture of bio-plastics. Sugar refinery waste and urea enhanced the manufacturing process using submerged fermentation. Pseudomonas aeruginosa produced maximum PHA on cane molasses and urea compared to other expensive sources of carbon and nitrogen in batch fermentation. Sugar cane molasses have the highest cell biomass and it is one of the carbon sources which produces maximum PHB when compared to other sources (Naheed & Jamil N., 2014).

The spent wash of molasses can also be used in the production of PHB biopolymer by the waste activated sludge method. Due to the high concentration of sugars in the waste, molasses can still serve as a low-cost carbon source for the commercial synthesis of biodegradable polymers such as PHB despite its toxicity caused by the presence of phenolic residues left after the fermentation and distillation of alcohol. Therefore, molasses can be served potentially as a cheaper substrate in the synthesis (Anshuman *et al.*, 2009). Further studies can be concentrated on the other methods of molasses spent wash treatment since the existing method was found to be quite difficult.

2.14 Waste Glycerol Derived from Industries

The research on the production of PHAs has been focused on utilizing pure carbon sources, such as sugars and fatty acids. In industries, considering the production costs many researchers have made efforts to make use of alternative renewable and cost-effective feedstock. Waste glycerol which is the by-product of biodiesel production is one of the potential feedstocks for the production of PHA polymers (Chengjun *et al.*, 2013). Glycerol is the most common plasticizer used worldwide because of its high plasticizing capacity and thermal stability at processing temperatures (Ana *et al.*, 2015).

Even though glycerol has been widely used in the cosmetics, food, and pharmaceutical industry, it is expensive to purify the crude glycerol for commercial applications. Hence, bacterial fermentation could be feasible to utilize low-value waste glycerol and produce value-added bioproducts (Abidin *et al.*, 2021).

Glycerol is transformed into PHB by a variety of natural PHA-producing bacteria when there are more carbon sources available and at least one of the other nutrients becomes deficient. Crude glycerol is known to be a sustainable and affordable source of fuel for the growth of bacteria and the synthesis of PHA. Therefore, to lower the cost of the PHA production process, crude glycerol from industries could be used as an alternative plasticizer.

2.15 Papermill Waste

One of the common waste resources deposited in landfills is papermill waste which got many organic molecules that can be converted to plastic in the replacement of petroleum plastic. In general, the papermill waste has some properties such as the presence of total chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), the concentration of ammonium, nitrite, nitrate, phosphate, and total suspended solids (TSS) and various composition of organic compounds are present. Especially the papermill waste is enriched with microorganisms which can be converted into bioplastics (Yang *et al.*, 2012). Generally, papermill wastewater is limited with the essential growth nutrients such as ammonium and phosphate however they arefound to be rich in organic carbon. Lignocellulosic waste is meant to be one of the most existing biomasses on the earth and serves as an ideal material for the degradation of soluble sugar in bioplastic production and the waste from papermill is supposed to have lignocellulosic biomass

(Huda *et al*., 2019). Hence, the paper waste can be processed as a feedstock for the production of bioplastic.

2.16 Keratin

The waste from farm animals is currently being used for various valuable purposes such as fertilizers, livestock feed and pet foods (Navina *et al*., 2018) but some of them are also disposed into landfills which leads to environmental pollutions. The body parts (legs, heads, viscera, bones and feathers) from these domesticated animals or bird species which were considered as waste can be served as a main source of animal protein (keratin). One of the most significant potential resources for producing biodegradable materials in particular is the feather (Liu *et al*., 2018). The United States produces more than 4 billion pounds of feathers as co-products each year, most of which are disposed of in landfills because they have few uses (Pavel *et al*., 2010). Utilizing these feathers for the production of bioplastic may help in increasing the value of feathers instead of disposing and the availability of raw material is also inevitable because the need for poultry production is increasing day by day (Tamrat *et al*., 2018). The keratin protein obtained from feathers is hydrophilic and biocompatible and can be used for the production of bioplastic (Alashwal *et al*., 2020). Therefore, the bioplastic produced from keratin can be used in various industries for food packaging purposes.

2.17 Sheep Wool

Sheep are meant to be domestic animals that are commercially used in many ways. The products from the sheep are milk, meat, wool, etc. in which wool plays a major role in the textile industries. Novel bioplastic films are derived from many sources, one of which is wool since it has keratin. Wool comprises 95% of keratin so it is a rich source of intermediate filament protein (IFP) which can be used as a raw material for the synthesis of biological materials (Jeanette *et al*., 2009). Wools are also composed of 90% keratin fibres which are characterized by the presence of cystine (R1-S-S-R2) residues and they can act as cross-linking points that provide rigidity and strength to the keratin fibres (Borja., 2019). These cross-linking do not allow keratin to dissolve in the water solution of concentrated salts because the R1-S-S-R2 crosslinks make the macromolecules insoluble. Therefore, mild oxidative methodologies are required to split the disulphide bonds and to extract the keratin in high yield which is used for the synthesis of bioplastic.

2.18 Seaweed

The stranded seaweeds possess various threats to marine wildlife like prevent the nesting of turtles and ensnare dolphins and fish in the coral reefs. Hence the removal of seaweeds in such places is necessary to protect marine animals and utilizing the removed seaweeds is essential to avoid waste accumulation in the environment. Seaweeds consist of numerous nutritional contents in them and thus seaweeds are used in various fields for various purposes (Sudhakar *et al*., 2021). The main content of seaweeds are polysaccharides (carrageenan, agar, and alginate) which can be extracted and utilized in the manufacture of bioplastics (Rajendran *et al*., 2012). They could be utilized to produce high-quality, biodegradable bioplastics because they are polymers derived from sugars that contain carbon and renewable biomass resources. The bioplastic from seaweed can be synthesized from polysaccharides of dried seaweeds by the hot extraction process. The bioplastic produce by this procedure was eco-friendly, cost-effective, and toxic-free which can match the quality of the various conventional plastics (Lim *et al*., 2021). Due to the availability and unique properties of seaweeds, they are often served as a replacement and alternative source for the synthesis of bioplastics.

2.19 Fish Waste

Fish waste, a major source of marine waste which can serve as a good source of protein to produce protein-based bioplastics as they are low-commercial value raw material thereby reducing the consequences of waste disposal in the environment (Araújoa *et al*., 2018). Fish proteins have remarkable properties like plasticity, elasticity and they also act as a good oxygen barrier which will enrich the bioplastic synthesis. The myofibrillar proteins (myosin and actin) can act as an excellent raw material in the synthesis of bioplastic which is present as a major source in fish waste. Due to the stiffness of the myofibrillar proteins, plasticiser like glycerol or sorbitol should be added in order to increase the flexibility. Though proteins are capable to form networks they also have some drawbacks because they have lesser mechanical properties compared to synthetic polymers, this can be rectified by using the desired amount of plasticiser that will help in enhancing the mechanical properties of the bioplastics (Siti *et al*., 2020). The biotransformation of protein from the fish waste into biodegradable plastics will help to reduce the fish waste being dumped in the landfill and also reduce the usage of synthetic packaging (Eleda *et al*., 2019 and Surya Parthasarathy *et al*., 2022).

2.20 Shells of Marine Species

Chitin is the vital structural component in the exosk eletons of crustaceans like crab, shrimp, lobsters (Hudso n et al., 2015), etc. and it is the second extensive polysac charide used as an excellent raw material in the synthesis of biodegradable plastics (Lorenz *et al*., 2016). Chitin is colourless, crystalline powder insoluble in water and oth er organic solvents (Pandharipande *et al*., 2016). The cra b shells contain 15-20% of chitin, 25% of protein and 40-50% of calcium carbonate. More than 1011 tons of chitin are produced per year in the marine environment (Divya S & Daniel RR., 2021). It is noted that two different typ es of processes were implemented for the extraction of c hitin among which the chemical extraction process produ ced pure chitin than the biological extraction process. It i s also illustrated that the bioplastic films produced from c hitin at various conditions have more tensile strength wh en compared to commercial plastics.

3. Conclusion

The interest in using plastic by the industries have been increased in the last few decades because the properties of the plastics can satisfy the need of some industries. Though, it has added advantage they are being a threat to the environment. Therefore, biodegradable plastics or polymers will be a suitable replacement for the sustainable world. Hygiene products such as diapers, sanitary napkins can also be manufactured from bioplastics. Bio-based plastics can also serve as a raw material for the production of artificial heart, hip joint, heart valve and finger joint. Biodegradable plastics can be used in various industries by modifying their properties according to their industrial usage and also in developing products with superior environmental performance. As the development of bioplastics is at the primary level once it comes into usage in mainstream markets and companies that can satisfy the customers, bioplastics can be an undeniable replacement for petroleum plastics (Alastair *et al*., 2013).

This review focused on the significance of biodegradable plastics, their benefits and drawbacks, as well as their uses and the recycling of different biological waste materials into biobased polymers. Though various biological waste resources have been used in the conversion of biodegradable plastic, many studies need to be improved further for the commercial utilization in near future. In the contemporary materialistic world, the newly created biodegradable plastics will be a novel substance. The use of bio-based plastic would be one of the important answers that may be put into place in the modern period, given the environmental degradation. By replacing current plastics with biodegradable materials, the generated wastes can be easily degraded, paving the way for a circular economy for a sustainable future and a greener environment.

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