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REVIEW ARTICLE

Bioplastics From Fruit Waste: A Trade Opportunity in a Green Future

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ABSTRACT

Bioplastics are biologically derived, biodegradable polymers. Food waste is a challenge for sustainable development as it can increase greenhouse gas emissions and other issues related to the environment. Meanwhile, plastic waste contributes significantly to environmental pollution. Because of increasing environmental concerns due to conventional plastics, the development of “environmentally friendly” materials has attracted extensive interest. Fruit waste is known to increase during fruit processing and manufacturing. The present study aims to explore the potential of fruit waste as a bioplastic material as an environmentally friendly alternative to conventional plastic. Most of the fruit wastes have the potential to be developed as bioplastics as they contain starch, cellulose, pectin, and other biopolymers. Some of the fruit waste is generated by the fruit processing industries, including banana peel, pineapple peel, durian seed, jackfruit seed, avocado seed, orange peel, jackfruit perianth, pomegranate peel and dragon fruit peel etc. The production of bioplastics from fruit waste offers the potential to indirectly address two issues, namely reducing plastic waste and fruit waste, at the same time, thereby promoting environmental sustainability. In order to overcome the challenges and develop workable methods for producing bio-based plastics, it is in fact necessary to step up innovations and research in this area. This eco-friendly strategy can reduce our dependency on conventional polymers made of fossil fuels and take us to a more sustainable future.

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1.INTRODUCTION

Plastic has become an integral part of our lives, but it also generates a lot of waste globally each year. (Muthaszeeret *al*. 2020). Plastics, metal and glass containers, worn-out machinery, food wrapping, old furniture, garbage, etc. are the major sources of land pollution (Modebelu *et al*. 2014). Today, plastics have become a serious environmental issue. Conventional plastics decompose very slowly, which can cause the original products to remain in landfills for hundreds or even thousands of years. (Maheshwari *et al*. 2013).

Non-biodegradable plastics create severe environmental problems and pose risks to both human and animal health. Millions of seabirds and other aquatic species have died as a result of plastic pollution. Since 2010, global plastics manufacturing has surged by 36%. This has generated significant interest in bio based plastics to meet global plastic demands (Nanda *et al*. 2022). Conventional plastics are produced by using non-renewable resources, including petroleum, coal and natural gas. It takes many decades to degrade in nature and also produces toxins during degradation. Therefore, it is necessary to produce plastics from materials that can be easily removed from our biosphere in an “ecofriendly” manner. It is termed bioplastics. (Sartika *et al*. 2018).

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Bioplastics are a renewable type of plastic because their constituents are made of biopolymers derived from agricultural resources, including starch, cellulose, proteins, and pectin. (Gustafsson *et al*. 2019). Starch is one of the major component of bioplastics. As starch is a renewable, readily available and inexpensive material, it is frequently employed in the form of biodegradable films for a range of purposes. (Alves *et al*. 2015). Many research studies using starches as matrix for bioplastics have confirmed the potential of the biodegradable polymer (Moro *et al*. 2017). There have been several authors who have used starch sources to develop bioplastic, such as avocado seeds (Ginting *et al*. 2018; Ramesh *et al.* 2021), jackfruit seed (Harahap *et al.* 2018; Santana *et al.* 2018;Kahar*et al.* 2019) and durian seed (Ginting *et al*. 2017) apple pomace (Gustafsson *et al.* 2019).

Bioplastic can be made from polymers derived from biological sources. Food waste is one of the biological sources that can be used to make bioplastic. It comes from the food processing industry or domestic consumption, such as pineapple peel, banana peel, durian seed, jackfruit seed, avocado seed, apple pomace, etc. The production of bioplastic from food waste has a double benefit: it can simultaneously address two issues, namely the reduction of plastic and food waste, thereby promoting environmental sustainability ((Ramadhan *et al.* 2020).

The amount of waste produced by the fruit and vegetable industries is considerably higher, with peels accounting for 25–30% of the total, followed by seeds, skins, shells, pods, cores, pulp, pomace, etc. (Rifna *et al.* 2023). If these fruit wastes are not handled properly, they can cause significant environmental concerns such as water and soil pollution, the greenhouse effect, eutrophication, global warming, and other health issues (Medeiros *et al.* 2020). These fruit wastes have potential uses in the development of bioplastics. Therefore, the production of bioplastics is a way to reduce and recycle waste after its useful life, and it also helps to reduce the pressure of negative impacts on the environment. (Ramirez *et al*. 2023).

The purpose of this study is to summarize any kind of fruit waste that proved can be developed into bioplastic material with potential applications in food packaging to promote environmental sustainability.

2. Fruit Loss and Processing Waste

According to the FAO of the United Nations, about 14% and 17% of the food produced worldwide is either lost or wasted each year. However, a new report from the World Wide Fund for Nature WWF and Tesco in 2021 stated that, around 2.5 billion tons of food are lost or wasted globally each year. This indicates an increase of over 1.2 billion tons from the prior estimate of 1.3 billion. According to these revised estimates, food waste is more than previously believed (33%), with an estimated 40% of all food produced going uneaten. According to the FAO, food waste would be the third-largest carbon dioxide emitter in the world if it were a nation, after China and the US. It is projected that fruits and vegetables, account for approximately 46% of food waste. (1400 million tons produced are wasted). (Nirmal *et al.* 2023). According to a Swedish survey, bananas are the fruit that is wasted the most because of brown stains or minor bruises in stores (Mattsson *et al.* 2018). It is estimated that 3.7 trillion apples are wasted worldwide annually. Two different types of waste generated from fruit processing: solid waste (peels/skins, seeds, stones, etc.) and liquid waste (juice and wash water). Fruit peel waste accounts for between 15 and 60% of the various types of fruit waste that are produced, and it is usually discarded (Zhang *et al.* 2020). For several fruits, such as the mango (30–50%), orange (30–50%), pineapple (40–50%), and banana (20%), a significant amount is often wasted. Some fruits, including banana, orange, mango, watermelon, and lemon, account for between 25 and 57 million tons of waste annually (Leong *et al.* 2022). If not properly managed, these fruit wastes can cause significant environmental concerns such water and soil pollution, greenhouse effect, global warming, eutrophication, and other health problems. (Medeiros *et al.* 2020). Therefore, waste recycling is essential for the effective utilization of fruit waste for production of bioplastics.

3.What are Bioplastics?

Bioplastics are defined as "plastic made from renewable resources or plastics that are biodegradable in nature" by the European Bioplastics Organization (EBO) (Bandara *et al.* 2023). Theseare similar to conventional plastics in all aspects with the additional quality being able to easily degrade and breakdown into natural and safe byproducts (Sartika *et al*. 2018). As it madefrom renewable sources can be naturally recycled by biological processes, thus protecting the environment by limiting the use of fossil fuels. Therefore, bioplastics are generally sustainable,

Table1. Comparative account of Conventional Plastics and Bioplastics

Properties	Conventional Plastic	Bioplastics
Origin	Hydrocarbon	Agricultural waste, Food waste, Fruit waste, Biowaste from effluent
Materials	Made up of finite materials, Fossil resources required, cannot be renewed	Made up of bio waste and based on renewable resources
Main products	Polyvinyl chloride (PVC), Polyethylene (PE), Polystyrene (PS), Polyethylene terephthalate (PET),	Starch, cellulose, lipid, chitin, protein based bioplastics; Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA), Polyhydroxy butyrate (PHB) polymers
Toxicity	It contains Bisphenol A (BPA), a hormone disrupter 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 energy uses during production.
Effect on environment	High greenhouse gas emission, Increases global warming, leads to abiotic depletion, reduces soil fertility	Low greenhouse gas emission, Mostly eco-friendly, no harm to abiotic factors, increases soil fertility
End of life	Plastic mixed with organic waste will end up in the landfills.	Bioplastics can be processed in waste facilities as compost.
Recycling	Recycling process is difficult.	Recycling process is less difficult.
Durability	It is more durable.	It is less durable.
Decomposition time	Traditional plastic can takes hundreds of years to decompose.	It takes only three to six months for full decomposition.

biocompatible, and biodegradable. Today, bioplastics have become essential in many industrial applications including food packaging, agriculture and horticulture, composting bags, hygiene and also found their use in biomedical, structural, electrical, and other consumer products. (Ashter, 2016). These are currently employed as packaging materials, but it will also be used in the future for producing various products such as electronics and vehicle parts (Shah *et al.*2021).

4.Types of Bio Plastics

Bioplastics refers to a broad family of materials having different origins, properties and applications. Any polymer is often described as a bioplastic if it is either bio-based (derived from renewable feedstock or microbes), or biodegradable (degrade or decompose naturally, under appropriate environmental conditions), or both. Thus bioplastics can be classified into three categories *viz.*, bio-based and biodegradable, bio-based and non-biodegradable, fossil-based and biodegradable. Another one is fossil-based and non-biodegradable which are known as conventional plastics.

4.1. Bio-based and Non-biodegradable

This group includes well-known commodity polymers made from bioethanol, such as polyvinyl chloride and polyethene. These bioplastics are chemically similar to their fossil based equivalents and are non-biodegradable in nature. However, they have a lower carbon foot print because they don't produce more carbon dioxide during incineration.

Bio-based polyamides, polyepoxides and polyesters (e.g. polytrimethylene terephthalate) are also belong to this group of bioplastics. (Bátori, 2018).

4.2. Bio-based and Biodegradable Plastic "The True Bioplastics"

These polymers are produced from biologically derived renewable resources. The majority of the plastics in this category are derived from natural polymers such as proteins, polysaccharides, and lipids from plants or animals origin. Another category of such material includes products of microorganisms such as poly hydroxybutyrate (PHB). Additionally, these plastics can be chemically synthesized from bio-derived materials, such as polylactic acid (PLA). These plastics are the true representatives of bioplastics owing to their biological origin and biodegradability. In order to make these plastics suitable for commercial use, the proper plasticizers are mixed with them. Two types of bio-based and biodegradable plastics are further described below (George *et al.* 2021).

4.2.1. Starch Based Bioplastic

The most significant polysaccharide polymer utilized to develop biodegradable films is starch since it has the ability to form a continuous matrix. The primary components of starch are amylose and amylopectin(Meenakshi *et al.* 2022). Starch is used as a raw material for manufacturing variety of industrial applications. As starch is energy reserve in plants, it is found in abundance. Starch imparts textural features and it has potential to form gel or film that makes it a valuable product for industrial applications. Starch is used in various industrial purposes namely emulsifying agent, defoaming agents, thickening agent and as sizing agents (Yazid *et al.* 2018).

In starch based plastics, starch can be utilized as native starch, modified starch or blended with other synthetic polymers. Starch-based polymers have a wide range of applications because of their thermoplasticity, flexibility, cost-effectiveness, water-repellent nature, and biodegradability. They are used to make pots, cups, sacks & packs, diaper films, air bubble films, and pharmaceutical packaging. (George *et al.* 2021). When combined with a plasticizing agents, starch has been widely employed for producing thermoplastic polymers. Therefore, plant wastes rich in this polymer have great potential for processing into conventional thermoplastic polymers (Merino *et al.* 2022).

4.2.2. Cellulose based Bioplastic

Cellulose is the most abundant organic compound in nature and a key component of plant cell walls. Depending on the type of plant, its content may vary from 50% to 90%. Cellulose derived from higher plants is a mixture of cellulose, lignin, hemicellulose, and other polysaccharides, including pectin and hemicelluloses. The acetates, butyrate and propionates of celluloses are abundantly used in the production of plastics. 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.Currently, lignocellulosic biomass and cellulose-rich food industry waste are regarded as cheap sources of cellulose to produce plastic. Important applications of cellulose based plastics include plastic films for LCD and antifog goggles; cellulose based coatings for metal and wood, printing inks, filters for window cartons, water-soluble films used for packaging medical capsules and detergent powders that readily dissolve in water. (George *et al.* 2021).Cellulose derivatives are polysaccharide made up of linear chains joined together by beta (1-4) glucosidic units. Cellulose derivatives utilized for edible films and coatings are Hydroxypropyl cellulose, Hydroxypropyl methylcellulose, Carboxymethylcellulose and Methylcellulose. They exhibit thermo-gelation which is the process whereby suspensions form gel when heated and return to their original consistency when cooled. (Shah *et al.* 2021).

4.3. Fossil-based Biodegradable Plastics

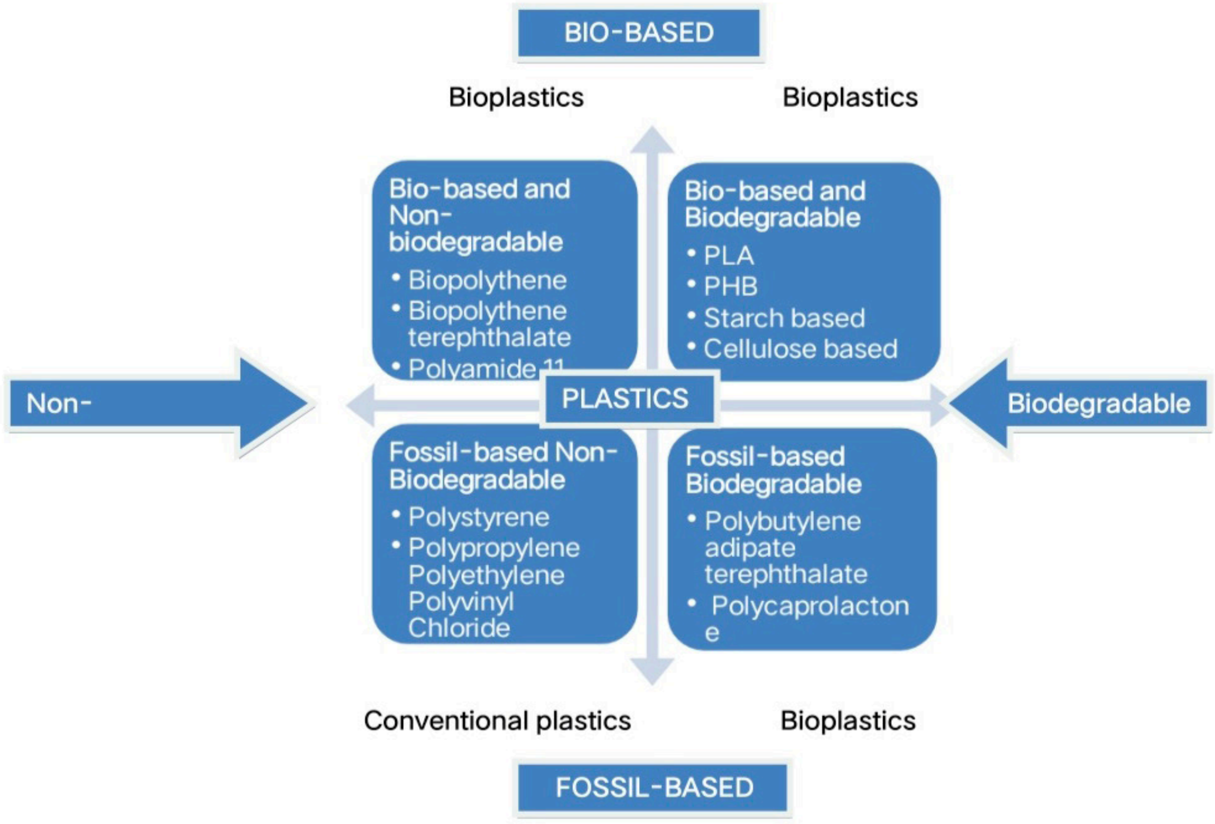
These polymers are a group of materials made from petroleum, and they are still capable of breaking down naturally. Polyesters in this group are polycaprolactone, polyglycolic acid, polybutylene adipate-co-terephthalate, and polybutylene succinate. These polymers have hydrolytic instability and biodegradability due to the ester linkage in their backbones(Rodriguezet al.2010)

4.4. Fossil-based Non-Biodegradable Plastics

These plastics are a group of materials that are derived from petrochemicalsand do not decompose naturally. Petroleum-based plastic is often durable, long lived and non-biodegradable. These are generally referred to as conventional plastics. (Sidek et al. 2019)

This group includes plastics like polyethylene, polyethylene terephthalate, polystyrene, polyvinyl chloride and polypropylene.

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



5. Different kinds of plasticizers used for the production of bioplastic

Plasticizers are a type of relatively non-volatile, low-molecular-weight organic compounds that are added to plastic polymers to reduce brittleness, reduce crystallinity, improve durability and toughness, and lower melting temperatures. These reduce polymer-polymer contact; due to this, the rigidity of the 3D structures is also reduced, which thereby improves the deformation ability without rupture (Tyagi & Bhattacharya, 2019). Different types of plasticizers, including polyols like glycol, glycerol, (Arfat, Y. A. 2017) sorbitol, fructose, sucrose, and mannose, as well as fatty acids like palmitate or myristate, are utilized in the manufacturing of bioplastics. Among these, the most widely studied and used plasticizer is glycerol because of its non-toxicity, low cost, and high boiling point (292 °C) (Shah *et al.* 2021).

6.General process of bioplastic making.

The process of bioplastic making may be different for each material utilized, the properties of the bioplastic produced, and the various product configurations. According to previous research, figure 1 summarized the complex process of bioplastic making. Each process included different methods, components, and compositions. (Ramadhan *et al.* 2020).

Pre-Treatment includes procedures including material grinding, drying, and hydrolyzation. Not all parts of the waste are used; only the starch and cellulose of the waste are extracted for use in the production of bioplastic. And the most important part is characterizing materials, including adding plasticizer agents, odor-controlling agents, and biological material. (Ramadhan *et al.* 2020).

7. Fruit waste used as bioplastic material

In the current world, where food is a scare resource, we can make bioplastics from non-edible parts. The majority of raw materials used to make bioplastics come from agricultural or farm products. Fruit waste is a significant material that can be used to develop biopolymers or bioplastics.

Things such as orange peel, pomegranate peel, banana peel, jackfruit perianth, durian seed

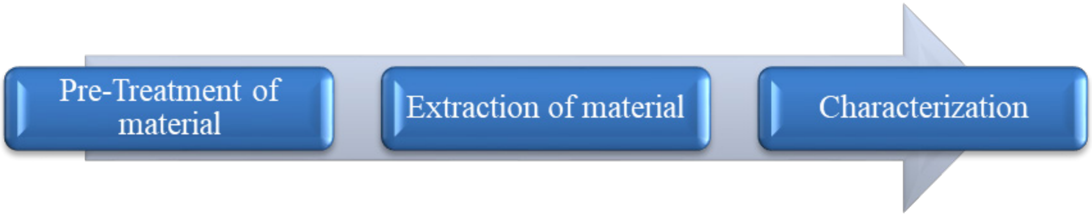
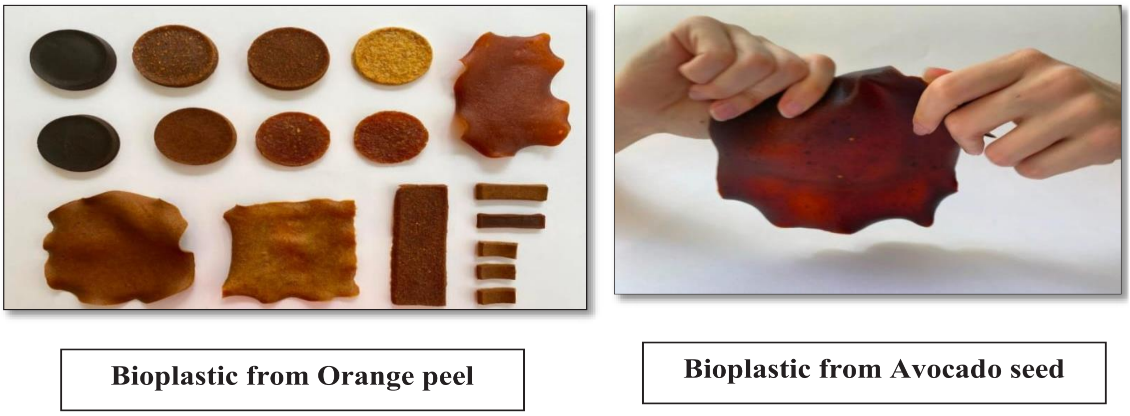


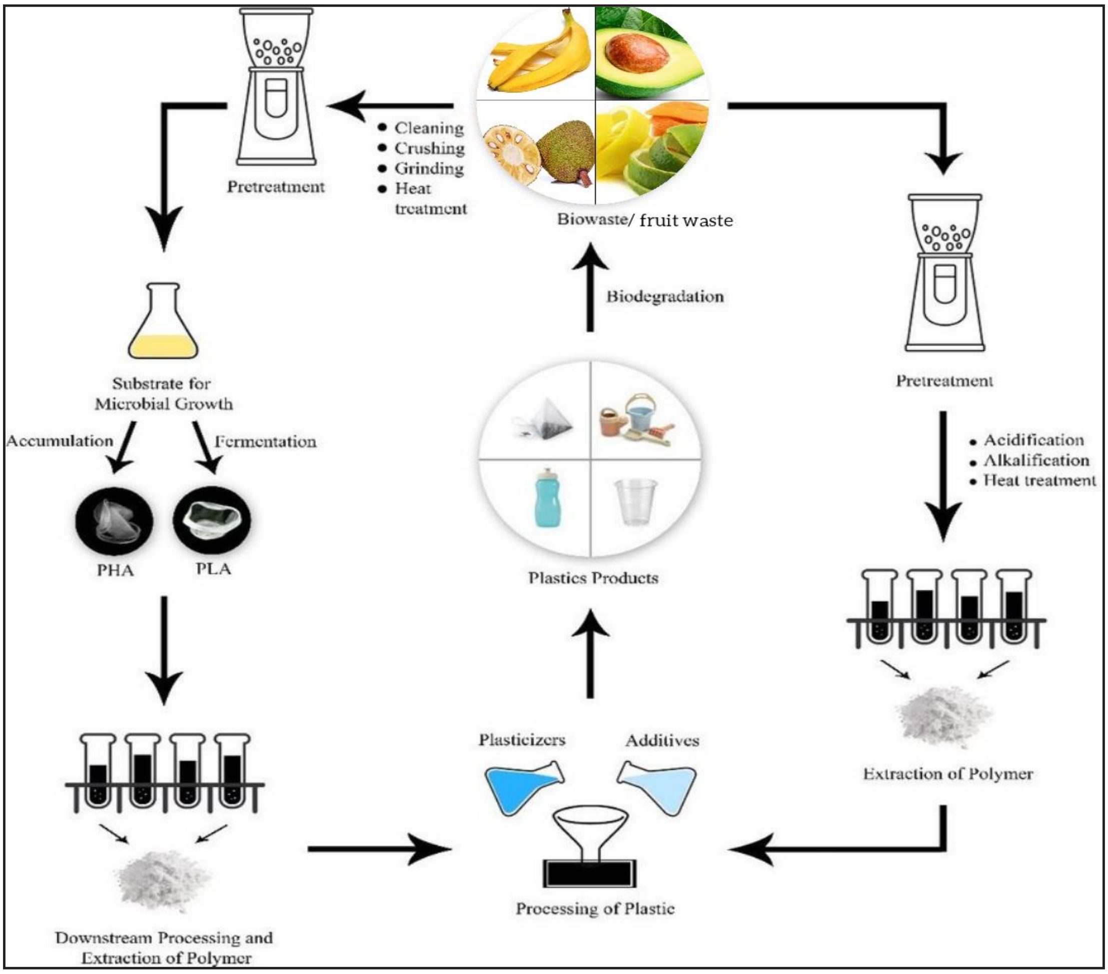
Figure 2. The general process of bioplastic making.



Bioplastic from Orange peel

Bioplastic from Avocado seed

Figure 3. Generalized Process of Bioplastics Production from Biological Wastes



etc. can utilized for the production of bioplastic. Bioplastic films made from feedstock derived from polysaccharide residue are very popular nowadays. These lignocellulosic feedstocks are useful for the manufacturing of bioplastic because they contain cellulose, hemicelluloses, starch, and pectin.

7.1. Banana peel

Banana peels, a byproduct of agricultural processing industries, can be used in making bioplastics as they contain cellulose, starch, pectin, and other polymers. Cellulose is modified to produce thermoplastic polymers by acetylation (cellulose acetate) (Rana *et al.* 2018).The pectin found in banana peel, ranging from 5% to 12%, has the potential to be used as a source for the production of bioplastics. (Abel *et al.* 2023).

Pectin is used in the production of bioplastics as an emulsifier that increases intermolecular bonds in the film. Citric acid has been added to banana peels to avoid browning so that pectin produced by banana peels is brighter. (Chodijah *et al.* 2019).

7.2. Apple pomace

Apple pomace represents 25% to 30% of the original weight of the apple (Ampese*et al.* 2023). Producing apple juice, cider, or wine results in the production of millions of tons of apple pomace annually throughout the world. Apple pomace is not suited for animal feeding or landfilling due to the acidic properties of the fruit and its high sugar and low protein content. (Perusselloet *al.* 2017). This residue can be utilized to make bioplastic due to its high moisture content and biodegradable organic content. Cellulose (7%–44%), insoluble lignin (15%–20%), starch (14%–17%), and pectin (4%–14%) make up the majority of the constituents of apple pomace. (Gustafsson *et al.*2019).

7.3. Pineapple peel

Pineapple peel is a byproduct of both the pineapple processing industry and domestic consumption. Cellulose, the primary constituent of the peel, can be extracted by refluxing it with acidic or alkaline solutions. Cellulose is a naturally occurring polymer with a homogenous chain structure made up of glucose units. Through the etherification process, cellulose can be converted into carboxy methylcellulose (CMC). (Chumee & Khemmakama 2014).

7.4. Durian seed

Durian seeds are a byproduct of food processing industries and a portion of the fruit that is not eaten because it is sticky and irritant to the tongue. Nevertheless, the seeds contain nutrients like protein, carbohydrates, fats, and minerals like calcium and phosphorus. Durian seeds contain starch, which has the potential to be used as a raw material for production of bioplastics. However, there are several drawbacks to starch-based bioplastics, such as lower mechanical strength and less water resistance. (Ramadhan *et al.* 2020).

Durian seed has a high starch content of 42.1%, making it a promising raw material for bioplastics. The biodegradable time was found to be between two and four weeks using durian seed starch as the raw material and glycerol as the exploration medium. (Irhamni *et al.* 2014; Retnowati *et al.* 2015; Jannah *et al.* 2021). Other plasticizers like polyethylene glycol (PEG) can increase the strain on bioplastic because it is thicker, stronger, and well-soluble in water. (Apriani *et al.*2022)

7.5.Jackfruit seed

Jackfruit seed, which makes about 8–15% of the jackfruit, has a high starch content, making it a potential food waste. (Kringel*et al.* 2020). It can be used as raw material for production of bioplastics. Studies on the production of bioplastics from jackfruit seed starch have been carried out. The jackfruit contained a moisture content of 6.04%, amylose content of 16.39%, starch content of 70.22%, ash content of 1.08%, amylopectin content of 53.83%, protein content of 4.68%, and a fat content of 0.54%. Starch, chitosan, and sorbitol were used in combination for producing the bioplastic. The best bioplastic had a tensile strength of 13,524 MPa and was obtained by the ratio of starch: chitosan (w/w) = 8:2 and a concentration of sorbitol of 25%. Meanwhile, glycerol is used as a plasticizer in other studies for the production of bioplastic from jackfruit seeds. The starch concentrations used ranged from 2-6% w/w, while the amount of glycerol per 100 grams of starch was 20–60 g. (Lubis *et al.*2017).

Jackfruit seed starch can be used as a base material for bioplastics with characteristics including low opacity, moderate water vapor permeability, and relatively high mechanical stability. (Santana *et al.* 2018).

7.6. Avocado seed

Avocado seed, which makes up 13-18% of the overall weight of the fruit (Siol&Sadowska, 2023) is a potential food waste due to its high starch content. Like jackfruit seed, this starch content can be used as a raw material for making bioplastics. The avocado seed starch had a starch content of 73.62 % and amylopectin content of 73.55 % so that avocado seed has potential to be plastic film material. (Ginting *et al.*2018). Chitosan and glycerol have been added to an avocado seed starch in a bioplastic development study.Bioplastics with glycerol as a plasticizer and chitosan as a filler have few cavities and a smooth, soft fracture surface (Ginting *et al.*2015).

7.7. Orange peel

About 50–60% of the leftovers produced during the manufacturing of orange juice are not used. The orange wastes contain valuable bioactive substances like cellulose and pectin that have the potential to be used to make bioplastics (Othman & Fadzil, 2021).The bio-plastic film made from orange peel was produced using simple laboratory techniques. The developed film blends with glycerol as a plasticizer have shown consistent and promising outcomes. This has excellent strength, flexibility, and disintegration in soiling conditions, has a rough morphology, and shows the film's biodegradability nature (Yaradoddi*et al.* 2022).

7.8. Jackfruit perianth

The waste of jackfruit (*Artocarpus heterophyllus*) perianth can be converted into environmentally friendly bioplastics. The composition of jackfruit perianth, sach as glycerol, cellulose and starch influence the properties of synthesized bioplastics. It has also been found that bioplastics with higher glycerol concentrations have lower tensile strength. This study shows that waste agricultural raw materials, such the jackfruit perianth, have the potential to be converted into bioplastic, an environmentally friendly substitute to plastics based on petrochemicals. (Muthaszeer *et al.* 2020).

7.9. Pomegranate peel

Pomegranate (*Punica granatum)* is a rich source of bioactive compounds which contains pectin-27%, cellulose-26.2%, hemicelluloses-10.8%, and lignin-5.7%. The polysaccharides in pomegranate peel undergo acid hydrolysis and are converted into monosaccharides, which then breakdown into cellulose, hemicelluloses and lignin components. These components are further utilized to produce bioplastics. (Chozhavendhan *et al.* 2020).

7.10. Dragon fruit peel

The skin of the *Hylocereus polyrhizus* is peeled off and eaten as fresh fruit. They are additionally processed into juice, jams, syrups, and other industrial goods. The peel makes up about 22% of the fruit, which is considered waste from the processing of dragon fruit (*Hylocereus polyrhizus*). (Taharuddin *et al.* 2023). The peel of dragon fruit contains around 10.8% pectin. Peels have not been used and are discarded as agricultural waste. According to several research, pectin from dragon fruit can be extracted and used to develop biofilms. (Listyarini*et al.* 2020).

8. Future prospects

In recent years, bioplastic has become a cutting-edge and environmentally friendly material. Although it is generally considered to be an appropriate substitute for conventional chemical-based plastics, there are still a number of issues that need to be addressed. These include improving mechanical properties such as heat and shock resistance, expanding the range of applications, enhancing processability, developing industry standards, and reducing production costs. In order to solve these challenges, scientists are presently investigating novel plasticizers and developing composite polymers to improve mechanical capabilities. Finding appropriate biological sources, particularly those found in waste products, is a vital approach to improve the sustainability of the production process. If these initiatives are successful, bioplastics might be used in more sectors, which would drive this industry's rapid expansion. Further development is anticipated with intensive study that would solve the issues with the technique now used to produce bioplastics and also eliminate our dependency on conventional polymers made from fossil fuels. While facing serious concerns about climate change and the exhaustion of resources, bioplastics might be a helpful step toward a more sustainable future. The bio-based plastics are environmentally friendly and also pave the way for organic waste management, in a more effective manner. Extensive research and innovative methods for producing these bio-based plastics would boost environmental sustainability and human life expectancy.

CONCLUSION

The use of renewable resources rather than petrochemical ones in the manufacturing of bioplastics is better for the environment and other forms of life on the planet. Petrochemical-based plastics have a number of drawbacks, including the fact that they pollute the environment and release harmful gases during production and recycling. Additionally, consuming food that has been packaged in plastic may result in cancer. Due to this, global interest is growing in the development of innovative biodegradable polymers from renewable natural resources. Instead of petroleum-based plastics, we should use bioplastic because it is renewable, biodegradable, sustainable, and environmentally friendly. Therefore, there is a great need to promote research and development in the field of bioplastics. However, bioplastics are not the only solution, changes in the way we buy, consume and dispose of plastic are also important.

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