**BIO-RESOURCES BASED SUSTAINABLE POLYMERIC MATERIALS AND COMPOSITES**

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**Summary**

Recently bio-based polymers and their composite materials have become of great interest for industrialists, and scientific researchers to deal with non-biodegradable synthetic plastic materials. Petroleum resource based synthetic non-biodegradable polymeric materials e.g. low-density polyethylene (LDPE), High density polyethylene (HDPE), linear low-density polyethylene (LLDPE), Polypropylene (PP), Polyvinyl chloride (PVC), Polystyrene (PS) etc. have demonstrated their uses in wide area of applications such as automotive, packaging, household, medical, agriculture, electrical insulation, etc. Their regular production and uses have arisen a matter of concern of their biodegradability and recyclability and this has become a serious issue to find an alternative of waste and non-disposable plastic products. To overcome this issue people have shown their keen interest towards natural resource e.g. plant and biomaterials-based polymer blends and composites to develop low cost, sustainable, biodegradable and eco-friendly polymeric products. The development of polymeric material from renewable resources has opened a door for various applications where bio-based polymeric materials demonstrate an attractive role, functions and sustainable end use properties. This review focuses on development and advantages of natural resources-based polymeric materials such as starch, cellulose, chitosan, lignin, seaweed, their blends and reinforcements such as plant based cellulose fibers, lignocellulose fibers, sisal fiber, crop fibers, leaves, wood fillers for fabrication of natural bio-based polymeric composites. The bio resource-based polymer blends and composites are capable to use in packaging sector, automotive, agriculture, single use household purpose, and utilities. Their future wide scopes are in commercial market to design them as biodegradable, compostable, environment friendly, cheaper, low waste, pollution less, and sustainable in end use performance.

**Keywords:** Biopolymer, Bio-composites, Sustainable, Biodegradable plastic

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**1. MAJOR SOURCES OF BIODEGRADABLE SUSTAINABLE POLYMER**

The biodegradation of biodegradable polymers is defined as chemical decomposition of substances, which is accomplished through the enzymatic work of microorganisms that lead to a change in chemical composition, mechanical and structural properties and forming metabolic products, which are environmentally friendly materials such as methane, water and biomass and carbon dioxide. Figure [1](https://www.nature.com/articles/s41529-022-00277-7#Fig1) shows biodegradation steps of polymers[1](https://www.nature.com/articles/s41529-022-00277-7#ref-CR3). Extracellular enzymes and abiotic agents such as oxidation, photo-degradation, and hydrolysis depolymerize long-chain polymers and create shorter chains (oligomers) in the first stage 2-4. The biomineralization process, in which oligomers are bio-assimilated by microorganisms and then mineralized, is the second stage. Either aerobic or anaerobic degradation can occur. Aerobic degradation takes place in the presence of oxygen producing CO2, H2O, biomass and residue. Anaerobic degradation is carried out in absence of oxygen producing CO2, H2O, CH4, biomass and residue[5,6](https://www.nature.com/articles/s41529-022-00277-7#ref-CR20).



**Biodegradation steps of polymers.**

**Fig. 1: The chemical biodegradation diagram.**

### *Classification of biodegradable polymers*

Biodegradable polymers may be categorized based on their origin and synthesis method, their chemical composition, economic importance, processing method and applications. They are categorized in this study based on their origin[7](https://www.nature.com/articles/s41529-022-00277-7#ref-CR24). Biodegradable polymers are classified into two groups based on their origin as indicated in Fig. [3](https://www.nature.com/articles/s41529-022-00277-7#Fig3). Natural biopolymers and synthetic biopolymers are made from natural resources and oil, respectively 8,9. Natural biopolymers are derived from renewable or biological sources such as animal, plant, marine, and microbial sources, while synthetic biodegradable polymers are manufactured chemically [10-12](https://www.nature.com/articles/s41529-022-00277-7#ref-CR25).



Schematic shows biodegradable polymers classification based on their origin and method of production.

* 1. ***Natural biodegradable polymers***

All organisms’ growth cycles result in the formation of biopolymers in nature. Polymerization reactions with a chain of enzyme-catalyzed growth from active monomers generated within cells through complicated metabolic processes are included in its production 13. They are naturally biodegradable and have good biocompatibility 14.

* 1. ***Biopolymers directly extracted from biomass***

Agricultural waste is a major source for the production of bioplastics, plasticizers and antioxidant additives. The main source of polysaccharides is plant-based agricultural waste where biopolymers such as cellulose, starch, and pectin are produced 15-18. The use of agro-waste as a feedstock for biodegradable polymer synthesis can reduce both the cost of producing biodegradable polymers and the waste treatment cost. Biopolymers are produced through several methods, namely microbial methods, blending of biopolymers, and chemical methods19. Biopolymers produced from agricultural plant waste have biodegradability, bio-functionality, biostability, and biocompatibility. They have wide range of chemical and mechanical properties that may be employed in several applications such as food packaging, biomedical applications, skincare, electrical electronics, vehicles and wastewater treatment 20-23.

* 1. ***Polysaccharides***

Polysaccharides, proteins, and lipids are found in numerous applications in biodegradable products. Potatoes, corn, and rice are basic sources of starch production, where the chemical composition and granules size of starch varies according to the source of production24. As shown in Fig. 4a, starch is a combination of linear (amylose) and branching (amylopectin) poly-(1,4) -α-glucose29. The ratio of amylose to amylopectin has a substantial impact on the physicochemical characteristics of starch25. Starch has poor mechanical properties, low impact resistance, water sensitivity, and brittleness properties. The properties can be improved by reinforcing the starch matrix with fibers or modifying the starch chemically or physically with other biodegradable polymers to enhance its properties 26-28. Starch is not completely soluble in water. It is partially soluble in water at room temperature, depending on the proportions of amylose and amylopectin 29-34. There are many advantages to starch biopolymers, such as high biodegradation, renewability, and good oxygen barrier properties that make them suitable in some commercial applications such as packaging applications, bags, cosmetics, adhesives, medical applications, and agricultural mulch films 35-38. One of the most common biopolymers is cellulose39. It contains reactive OH groups in the backbone 40. Cellulose is a polysaccharide with a molecular structure that is similar to starch. However, d-glucose units are attached to β-glycosidic bonds in cellulose. In starch, d-glucose units are linked to -α-glycosidic bonds. As illustrated in Fig. 4b, cellulose consists of polymer chains made up of unbranched β (1 → 4) connected D-glucopyranosyl units 41. Cellulose is the primary component of lignocellulosic plant cell walls. Hemicellulose, lignin, and other carbohydrate polymers are components of a gel matrix embedded with cellulose which exists in the lignocellulosic materials42. Cellulose and cellulose derivatives are ecologically friendly materials that are widely utilized due to their ability to decay, compatibility with other materials, and regenerate. Because of cellulose’s hydrophilic nature, moisture absorption causes the material’s mechanical characteristics to deteriorate. As a result, cellulose derivatives are created through chemical modification, in which bonds are formed between the reagents and the OH groups in the cellulose improving solubility and mechanical characteristics by reducing cellulose’s hydrophilicity43. Cellulose and its derivatives are used in different applications such as fiber industries, wood products, textile, and pharmaceutical industries44.



Chemical structure A. STARCH B. CELLULOSE

* 1. ***Polypeptides (Proteins)***

Proteins are natural polymers produced from various vegetables and animals. Collagen is a protein found in both vertebrate and invertebrate connective tissue. It accounts for around half of all human protein. Collagen has a hydrophilic nature as a result of the enormous substance of essential, acidic, and hydroxylated amino corrosive buildups that lipophilic deposits45. Collagen properties are exceptionally compelling in many fields, for example, leather chemistry, surgery, pharmaceutical industries like capsule production, etc.46-48.

Biopolymers derived directly from naturally occurring or genetically engineered organisms

Microorganisms are a source for research on bioplastic materials and biopolymers that use agricultural wastes as a medium for growth. Example of microbiological compounding plastic is polyhydroxyalkanoate (PHA), which is produced from various groups of bacteria and cheap renewable resources. It is completely aerobic decomposed by microorganisms30. polyhydroxyalkanoates are produced from a biodegradable aliphatic polyester family. They are formed in nature and produced directly by bacterial metabolism 49-51. They are genuinely biodegradable and profoundly biocompatible thermoplastic materials and can be developed from a variety of renewable resources. Polyhydroxyalkanoate is the potential alternative to the non-degradable polyethylene and polypropylene. Poly(3-hydroxybutyrate) (PHB) is the most representative member of this family 52-55. It is a natural polymer that formed by various chains of bacteria. It is produced from low-cost, renewable feedstock and without causing much impact on the environment. It is degraded in anaerobic and aerobic conditions and it doesn’t produce any poisonous materials from its degradation56. Copolymer of hydroxybutyrate (PHB) and hydroxyvalerate (HV) is known as poly(3-hydroxybutyrate)- hydroxyvalerate (PHBV). It is a highly crystalline polymer. By increasing the HV unit content, the melting point, the glass transition temperature, the crystallinity and the tensile strength decrease but the impact strength increases. The copolymer PHBV is less brittle than PHB. The degradation rate of PHBV is higher than PHB 57-60.

* 1. ***Synthetic biodegradable polymers***

Synthetic biodegradable polymers are produced by conventional polymerization procedures such as aliphatic polyesters, polylactide, aliphatic copolymer61. Due to the appropriate degradation time and their production in industrial scale, the degradable polyesters are considered as the most potential materials utilized comparing to conventional plastics. They are produced in several forms such as polylactic acid, polycaprolactone and polybutylene succinate. They have low ecological contamination62. More than 90% of the biopolymers are polyester as they contain easily hydrolyzable bonds of esters. Synthetic biodegradable polymers may be categorized into bio-based polymers like PLA and oil-based monomers such as PCL 63,64.

* 1. ***Aliphatic polyester synthesized from bio-derived monomers (water-based monomers)***

The most significant biodegradable polymer is polylactic acid (PLA)3. It is well-known for being biodegradable and biocompatible polymer29. It is synthesized from renewable materials such as potato starch, wheat, rice bran corn and biomass 65-68. Polylactic acid is linear aliphatic polyester thermoplastic polymers69. Polycondensation and ring-opening polymerization of lactic acid monomers are two processes that may be used to synthesize PLA70. PLA’s high molecular weight is achieved by polymerization of ring-opening. The final properties of the polymer can be controlled using this method71. Lactic acid monomer exists in three diastereoisomeric structures which are D-lactide, L-lactide, and meso-lactide (DL-lactide)72. Mechanical, thermal and biodegradable properties of PLA dependen on the selection of stereoisomers distribution within the polymer chain. PLA is used in many applications such as interference screws, sutures, dental, ligating clips, bone pins and rods73.

Polyglycolic acid (PGA) is a linear aliphatic polyester that is synthesized by polymerization of ring-opening of cyclic glycolide monomers74. It is a thermoplastic and biodegradable polymer. The degradation process of this polymer takes place in two stages. In the first one, water is dispersed in the amorphous regions of the polymer matrix where the ester bonds are separated. In the second stage, crystalline segment of the polymer gets vulnerable to hydrolytic attack75. This polymer is used in several applications such as tissue engineering, medical devices, and drug delivery76. Glycolic acid monomers (GA) are copolymerized with L-lactide and LD-lactide (LA) generating poly(lactide-co-glycolide) (PLGA). The rate of degradation decreases when the L/G proportion increased77. Mechanical and chemical properties are controlled by adjusting the ratio of monomers in the combined polymerization of the PLA and PGA without affecting the compatibility and biodegradability. The degradation of the PLGA takes place by hydrolysis of the ester bond and to form LA and GA which are eco-friendly materials78.

* 1. ***Aliphatic polyester synthesized from synthetic monomers (petroleum-based monomers)***

Polycaprolactone (PCL) is a biodegradable synthetic linear aliphatic polyester. It can be synthesized by polymerization of ring-opening of caprolactone monomers within the sight of metal alkoxides catalysts. Aluminum isopropoxide and tin octoate are common catalysts used in polymerization process79. Polycaprolactone is dissolved in numerous solvents such as methylene chloride80. The melting point of PCL is between 58-60 °C. It is degraded by the activity of anaerobic and aerobic microorganisms. The degradation rate of PCL depends on the level of crystallinity and its molecular weight81. This polymer is used in medical fields such as tissue engineering, long-term drug and vaccine delivery vehicles82. The biodegradability of PCL can be improved by copolymerization with aliphatic polyesters. PLA and PGA copolymer has lower crystallinity and melting point compared with the homopolymer83.

Polybutylene succinate (PBS) can be prepared by polycondensation of 1,4 butanediol with aliphatic dicarboxylic acid succinic acid84. It is a thermoplastic aliphatic polyester that has a melting point between 90–120 °C. It is decomposed by a hydrolysis mechanism22. Because PBS is crystalline materials, it degrades slowly. It is normally blended with different materials such as adipate copolymer which acquiring polybutylene succinate adipate (PBSA)85. This copolymer has a higher degradation rate than PBS86.

1. **Biodegradable polymer blends and composites**

The main characteristics of biodegradable polymers are their primarily hydrophilic nature, high rate of decomposition, and potentially undesirable mechanical qualities. These properties could be improved by mixing natural and synthetic polymers87. Blending polymers is a category of substances where two polymers at least are mixed collectively to produce a new material with various physical properties. The purpose of mixing two or more polymers is to develop a blend that combines each polymer’s preferred properties88. The preparation of biodegradable polymer blends is normally associated with the blending of a thermoplastic resin with biodegradable one. These types of blends are expected to be more biodegradable than conventional plastics89. After the degradation process of the biodegradable materials, the residuals components are more ecologically friendly and do not cause environmental pollution.

* 1. ***Natural fibers***

Natural fibers are perfect reinforcing materials for polymer composites (thermoplastics, thermosets, and elastomers). Natural fiber-reinforced polymer composites are gaining popularity due to their excellent mechanical properties and considerable manufacturing benefits, as well as the fact that they provide a solution to environmental contamination. Composites based on natural fibers have better impacts in the industry due to these fibers have high specific properties and low density. They don’t have health hazards because of they are non-toxic90. Natural fibers are renewable materials, relatively high in tensile strength, low-cost, and light91. Natural fibers have become a substitute for non-renewable and expensive synthetic fibers (glass, carbon and kevlar fibers) in different applications because of environmental aspects and their properties as shown in Fig. 5. Natural fibers contain some desirable properties, including high specific strength and modulus, flexibility during treatment, and excellent corrosion resistance92. However they show some limitations such as high anisotropy, moisture absorption, limited compatibility with conventional resins, and inferior homogeneity when compared to glass and carbon fibers93. For centuries, natural fibers used in several applications such as clothing, making baskets, ropes and various parts of automobiles94.

***2.2 Classification of natural fibers***

Natural fibers may be categorized based on their sources95. Natural fibers come from three main sources namely; animal, plant, and mineral materials96. Plant fibers include bast (stem) fibers, seed fibers, leaf fibers, fruit fibers, core fibers, cereal straw fibers, wood fibers and other grass fibers. Animal fibers include hair and wool. Mineral fibers such as asbestos and glass fiber. Figure 6a, b presents the classifications of the different natural fibers and cell wall of natural plants repectively97.



a Classification of natural fibers.

The plant fibers can be categorized into bast fibers, fruit fibers, leaf fibers, grass fibers, seed fibers, wood fibers, and stalk fibers. Bast fibers like ramie, hemp and flax. They come from the skin and bast around the plant stem. Fruit fibers that are collected from fruits such as coconut and palm. Leaf fibers that are extracted from leaves such as sisal, pineapple, abaca and banana. Seed fibers that are developed from seeds and seed shell such as kapok and cotton. Stalk fibers which are generated from the stalks of the plants such as wheat, rice, and corn. Grass fibers include bamboo and bagasse. Finally, wood fiber (hardwood and softwood)98-100.

* 1. ***Cotton fiber***

The purest form of cellulose is cotton. Cotton is hydrophilic. It has high elastic, flexibility and elongation at break. It is degraded by acids but it has resistance to alkalis. Cotton has low microbial resistance however the fibers are highly resistant to beetles and moths. Cotton is burning very fast101. Although cotton fibers are widely used, their mechanical performance suffers behind other natural fibers, notably different types of bast fibers. This can be attributed to the low degree of fiber orientation.

* 1. ***Coir fiber***

Coir is developed from the coconut fruit. It is found between the outer shell of the coconut and its husk. Among several natural fibers, coconut fiber has many desirable properties such as durability, high hardness, acoustic resistance, resistance to fungi and moths, and hardly burns. Also, this fiber is more moisture resistant than other natural fibers. It was reported that the coir fiber has saltwater and heat resistance102.

* 1. ***Flax fiber***

Flax fiber is the strongest fiber comparing with the other natural fibers. It is a renewable and biodegradable material. Great attention increased for flax fiber-reinforced plastic composites because of its great toughness, high strength, stiffness, low density, and bio-degradability. When compared to E-glass fiber, flax fiber has a higher specific tensile strength103. Flax fiber is widely used in several applications such as towels, carpets, ropes and fabrics. Also, flax fiber has been used in biocomposites fabrication104.

* 1. ***Kenaf fiber***

The outer (bast) and inner (core) fibers of the kenaf plant are used to produce kenaf fiber. Kenaf fibers are used in polymer matrix composite as reinforcement materials. It is non-abrasive during manufacturing, has a low density, and good specific properties. It is also biodegradable105. On the other hand kenaf fibers are rough, brittle, and hard to process. It is widely used in textiles, paper materials, ropes, absorbents, and building materials106.

* 1. ***Hemp fiber***

Hemp fiber belongs to the bast fiber family. It is used in polymer composites reinforcement67. It consists of 55-72% cellulose, 8–19% hemicellulose, 2–5% lignin, 4% minerals and less than 1% wax. It has excellent mechanical strength, elastic modulus and moisture resistance107. Hemp fiber has chemical composition comparable to flax fibers, however flax is less resistant to moisture than hemp. Hemp fiber has a toughness that is roughly 20% greater than flax, although they have a poor elongation108. Hemp fiber is used to produce paper, fabrics, construction materials, plastic and composites.

* 1. ***Jute fiber***

Jute fiber is extracted from the ribbon of the stem. Jute fiber has wood-like properties. It has good mechanical and thermal properties, high aspect ratio, high strength to weight ratio and good properties of insulation. Jute has a microorganism’s resistance, but it is sensitive to photochemical and chemical attacks. Jute fiber is brittle because of high content of lignin and a small extension to break110. It has tensile strength lower than flax or hemp. Exposure to sunlight causes loss of the tensile strength of the fiber and has little resistant to acid and moisture. Jute is the plant fiber with the highest hygroscopicity. Jute is silky texture, biodegradable material and resistant to fire and heat which makes it adequate for use in industries. It is used in travel luggage, fashion, furnishings, carpets and other floor coverings. Jute fibers may be used to strengthen polymer composites (thermoset and thermoplastic)109.

* 1. ***Ramie fiber***

Ramie fiber is white in color, very fine and silk-like. Ramie fiber is naturally resistant to germs, insects, and mildew. Ramie fiber is not harmed by mild acids and stable in alkaline media. The physical properties of ramie fiber showed high tenacity, high luster and brightness111. The fiber has an exceptional strength which slightly increases when wet. Ramie fiber is gaining attention as polymer matrix reinforcement in composites. Natural fiber has much less density than that of synthetics fibers.

* 1. **Sisal fiber**

The sisal fiber comes from the sisal plant leaves which are a hard fiber46. As compared to glass fiber, sisal fiber has a higher strength and stiffness112. Sisal fibers include a number of environmentally friendly benefits such as low density, excellent specific modulus, and strength. These advantages make them appropriate for use as reinforcement in composites. When the temperature of the sisal fiber increased, the tensile strength, modulus, and toughness for fiber decrease. It is smooth, yellow, straight and degraded easily in saltwater. The fiber increases the toughness of polymer than increasing the modulus and strength. The sisal fiber composites had maximum toughness than other fibers113.

***3.0 Pineapple leaf fiber (PALF****)*

PALF is made from the leaves of the pineapple plant. It’s a cheap waste product from pineapple farming. PALF consists of high content of cellulose about 70-82%, polysaccharide, and lignin. PALF has superior mechanical properties because of the high content of cellulose53. As compared to cotton, dyes faded more quickly due to the high content of lignin and wax materials in pineapple leaf fiber. Also, dyes difficult to penetrate due to the high coarseness of PALF.

***3.1. Abaca***

The abaca is a banana species. that comes from the leaf sheaths of the banana plant. It is yellowish-white in color and lustrous fiber. It is the strongest fiber among all other plant fibers. Abaca tensile strength is twice times higher than sisal and three times higher than cotton. It is resistant to degradation in saltwater than other fibers, so it is preferred to use in marine applications. Abaca fibers are used in many applications such as manufacturing ropes, bags, slippers, placemats and doormats. Also, abaca fiber is used as a reinforcement of composites114.

***3.2. Bagasse and bamboo***

After sugar is extracted from the sugarcane stalk, bagasse is a fibrous residue that remains. It is used in many applications like biofuel in the production of renewable energy and used as a natural fiber-reinforced polymeric composite. Bamboo fiber is a kind of cellulosic fiber. It has eco-friendly characteristics such as high growth rate, lightweight, high strength and it is a biodegradable material. It is used in many applications such as flooring to ceiling and transportation, furniture manufacturing, etc. Also, it is used as a reinforcement of composites115.

***3.3. Palm fiber***

It is biodegradable, compostable, and has the potential to break down into its essential parts and return to the environment naturally. Palm fiber has five times the tensile strength of structural steel and is comparable to flax, hemp, and sisal. It has better vibration dampening and acoustic insulation than glass and carbon fiber as well as better heat insulation than carbon60. Palm fiber has a cellulose purity of up to 70% and a thermal stability of up to 226°C.

***3.4. Animal fibers***

Animal fibers are the most significant natural fibers after plant fibers. They are employed in composites as reinforcement116. Animal fibers include mainly three types: hair, avian and silk fibers. Animal hair fibers are obtained from animals and hairy mammals such as horses, sheep, and goats. Silk fibers are obtained from insects while preparing cocoons or from dried saliva from insects. Avian fibers are produced from bird feathers.

***3.5. Structure and composition of natural fibers***

Natural fiber cell walls are made up of three layers: a main cell wall, a secondary cell wall, and an intermediate cell wall known as lumen117. Fig. 6b depicts the structural organization of a natural fiber cell wall. This structure is known as microfibril125. During cell formation, the wall of the primary cell is the first layer formed. Secondary walls S1, S2, and S3 are the three layers that make up the second cell wall. The lumen layer is responsible for the transportation of water126. The cell walls are formed of a semi-crystalline cellulose microfibril, hemicellulose, lignin, wax, pectin and water-soluble compounds118.

The physical properties of the fiber are connected to the inner structure and components of the plant material that is being used. The fiber of plants is lignocellulosic structures which are consist of hemicelluloses, cellulose, and lignin, as well as pectin, protein, wax, ash, tannins, and inorganic salts. These components are vary according to the fibers sources, growth conditions, age of plant and processes of digestion129. The chemical composition of some of the common natural fibers is presented in Table 1. Cellulose content of fibers is the most important factor in determining their characteristics and mechanical performance when utilized as reinforcement in composites. In contrast to cellulose, an increase in non-cellulose components causes a decrease in fiber strength and modulus, which has severe consequences for composites reinforced with natural fibers119.

# Table 1 Some natural fibers’ chemical composition

From: [Recent advances in biodegradable polymers for sustainable applications](https://www.nature.com/articles/s41529-022-00277-7)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Fiber** | **Cellulose (wt %)** | **Hemicellulose (wt %)** | **Waxes (wt %)** | **Lignin (wt %)** | **Pectin (wt %)** | **Reference** |
| Cotton | 89 | 4 | 0.6 | 0.75 | 6 | [79](https://www.nature.com/articles/s41529-022-00277-7) |
| Flax | 71 | 18.6–20.6 | 1.7 | 2.2 | 2.3 | [77](https://www.nature.com/articles/s41529-022-00277-7) |
| Kenaf | 53.5 | 21 | — | 17 | 2 | [79](https://www.nature.com/articles/s41529-022-00277-7) |
| Jute | 61–73.2 | 13.6–20.4 | — | 12–16 | — | [59](https://www.nature.com/articles/s41529-022-00277-7) |
| Hemp | 81 | 20 | 0.8 | 4 | 0.9 | [79](https://www.nature.com/articles/s41529-022-00277-7) |
| Ramie | 68.6–76.2 | 13.1–16.7 | 0.3 | 0.6–0.7 | 1.9 | [77](https://www.nature.com/articles/s41529-022-00277-7) |
| Abaca | 62.5 | 21 | 3 | 12 | 0.8 | [79](https://www.nature.com/articles/s41529-022-00277-7) |
| Sisal | 67–78 | 10–14.2 | 2 | 8–11 | 10 | [77](https://www.nature.com/articles/s41529-022-00277-7) |
| Coir | 46 | 0.3 | — | 45 | 4 | [79](https://www.nature.com/articles/s41529-022-00277-7) |
| PALF | 70–82 | — | — | 5–12 | — | [77](https://www.nature.com/articles/s41529-022-00277-7) |

***3.6. Applications of biodegradable polymer***

The use of biodegradable polymers is rapidly growing with a global industry worth many billions of dollars annually120-122. Biodegradable polymers are used in a variety of applications, including food packaging, computer keyboards, automotive interior parts, and medical applications like implantable large devices, medical delivery and tissue engineering. Figure [7](https://www.nature.com/articles/s41529-022-00277-7#Fig7) shows various applications of biopolymer materials123,124.



**Fig. 7: Applications of biodegradable materials**

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