Biodegradable Fibers, Polymers, Composites and Its Biodegradability, Processing and Testing Methods

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Abstract The worldwide awareness of the environment urged the search for new composites based on bio fibres. As a result, the focus shifted back to natural fibres, which are biodegradable and typically less expensive than synthetic fibres.Besides, there exists a huge amount of agricultural waste suitable to be used as bio fibre composite materials. Such composites find a wide application, for instance in the automotive industry, structural components, panels, noise control, acoustic wall, agro-fibres biocomposites, wind turbine blades, and many more. Synthetic polymers or eco-friendly polymers, such as poly(glycolic acid), poly(lactic acid), and their copolymers—poly(lactic-co-glycolide) or poly(l-lactic acid), polydioxanone, and poly(l-lactic acid), can be used to strengthen these fibres (caprolactone).The choice of both components' biodegradable in the bio-composites becomes crucial from the environmental perspective. This chapter covers a wide range of topics, including data on fibre/polymer composites and/or bio-composites, as well as the design of fibre composites. Also, this chapter reviews the natural fibre/reinforced polymers (NFRPs) degradability.

Keywords Biodegradable polymer · Structural designs · Bio-composites · Poly(lactic acid) (PLA)

Abbreviations

PLA	Poly(lactic acid),
PHAs	Polyhydroxyalkanoates,
PHB	Polyhydroxybutyrate,
PHBV	Poly(hydroxybutyrate-co-hydroxyvalerate),
PCL	Polycaprolactone,
PBAT	Poly(butylene adipate-co-terephthalate),

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PBS	Poly(butylene succinate),
PE	Polyethylene,
PP	Polypropylene,
PET	Poly(ethylene terephthalate),
PEG	Poly(ethylene glycol),
NR	Natural rubber,
LCP	Liquid crystal polymer,
LDPE	Low density polyethylene,
LLDPE	Linear low density polyethylene,
HDPE	High density polyethylene,
HMWHDPE	High molecular weight high density polyethylene,
MBS	Methacrylate-butadiene-styrene terpolymer,
PVC	Polyvinyl chloride,
TPU	Thermoplastic polyurethane

1 Introduction

The bioeconomy is defined as the activity related to the design of biodegradable material using biological resources materials and it has been adopted widely in USA, EU, and Canada [1]. Bioeconomy is needed for the low carbon economy worldwide. The current bioeconomy market has been estimated at € 2.4 billion [2]. Biocomposites are used in numerous industries to produce variety of items, such as construction materials, sporting goods, and consumer electronics. The advantage of the biodegradable composite may be summarized as [3–7]:

- using renewable biodegradable sources,
- low energy consumption,
- cheaper production composite,
- reasonable specific strength and specific elastic modulus,
- availability in many countries across the globe,
- biodegradable product recycling is possible,
- reuse of agricultural waste,
- recycle natural fibre products.

Many countries have instituted laws to promote recycling and turned out into green products [3] in several applications such as various civil engineering locations including roofing and bridges, thin sheets, shingles, roof tiles, prefabricated shapes, panels, curtain walls, precast elements. Cement bonded wood fibre formed from wood fibres in cement matrix is used for the manufacturing of panel sheet bricks as thermal isolators [8–16]. Table 1 gives some products of fibre/polymer composites. The global natural fibre composites market size, valued at US$, will reach about 8 billion [17, 18]. The fibres considered are wood, cotton, flax, hemp. Wood composites are the most popular, followed by cotton, flax, and kenaf fibre. The fibres used

Table 1 Natural fibre/polymer composite applications [3, 10–17]

Product	Reinforcement	Applications	Product	Reinforcement	Applications
Fibre boards	Non-woven, fabrics	Automotive interiors, furniture	Granulate of natural fibres blended with thermoplastic resin	Natural granulated fibres	Pallets, packages, appliances,
3-D shaped fibre boards	Natural fibres, non-woven mats	Automotive interiors, furniture	Boards	Agriculture residues	Furniture, panels, electric wire
Medium density fibreboard (MDF)	Bagasse mixed with other agricultural fibres	Solid wood replacement	Boards	Mix of natural fiber and glass fibres	Boats, water containers, storage grains, etc
Pultrusion profiles	Natural fibres fabrics	Different profiles	Roof shingles	Natural fibres bundles, Non-woven mats	Civil engineering applications
Long fibre reinforced thermoplastic	Natural fibres, roving or yarns	Different profiles as replacement for solid wood	Cellular Concrete	Rice, sisal, jute, sugarcane bagasse, ramie residues	Interiors in high buildings for weight reduction
Molded products	Nonwoven mat	Door siding, automotive industry, panels			

may be in the form of loose fibres, granulated natural fibres, natural fibres bundles, woven fabric, nonwoven fabric, and other forms of fibrous assembly. The natural fibre/polymer composite (NFPC) that can be made from fibres in different forms, yarns, woven or nonwoven, knitted, braided fabrics, is used as reinforcing to form the three-dimensional structure of the composite. The matrix is a polymer that gives the final rigid form of the composite and protects fibres from the surrounding environment. The purpose of the matrix is to keep the fibrous structure in final form through adhere the fibres together and redistribute the applied stress on the fibrous structure so that the applied stress is supported by all fibres in the composite cross-section [5, 19, 20]. Furthermore, a large amount of agricultural waste can be used to make acceptable biodegradable composites [3, 18]. For example, agricultural waste from wheat and rice straw amounts to roughly 710 million metric tonnes and 670 million tonnes, respectively, per year [3, 24–27].

Agriculture and forestry produce 11.9 billion tonnes of dry matter each year, with agriculture producing 61% and forestry producing 39% [28–33]. This is besides the recycled waste of the textile garment (In USA 16.9 million tons, 11.15 million tons were landfills). According to Nova-Institute [34, 35], demand for bio-composite board materials would increase at an ascending rate. Figure 1 demonstrates the

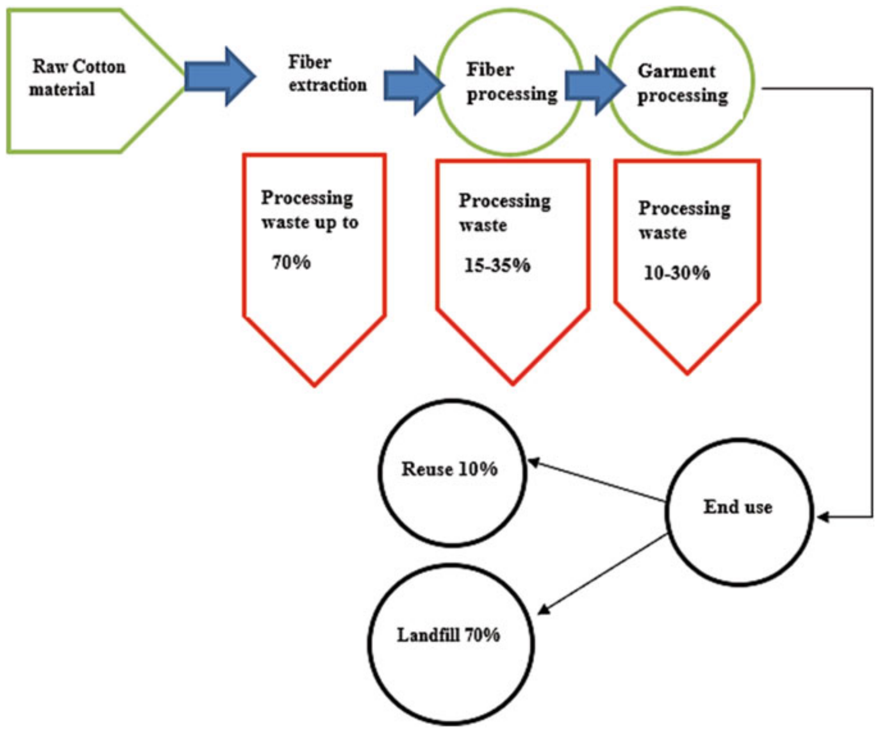


Fig. 1 Distribution of material flow in the cotton production chain

approximate percentage of the waste extracting during the life cycle of cotton fibres, which indicates most of the fibres will be landfilled.

2 Biodegradable Composite

The principle of the circular economy has gained great attention in the last decades, and environmental protection changes the scenarios of the material used for the formation of the different parts constructions, replacing the metal materials with composite materials, and further progress to use biodegradable composites. Replacing manmade fibre decreases the environmental impact of composite materials. The BioSource materials and biodegradable polymers as an alternative to traditional synthetic polymers will result in the biodegradable composite. The choice of both matrix and fibres being biodegradable results in biocomposites.

2.1 Biocomposite Reinforcements

The composite may be constructed in various shapes from the different types of fibres, either in 2-D or 3-D structures.

- Fibre-reinforced polymer
  (short or continuous filament),
- Yarns reinforced polymer
  (spun or multifilament),
- 2-D fabric reinforced polymer
  (woven or nonwoven fabrics),
- 3-D fabric reinforced polymer,
- Particle reinforced polymer
  (whisker, microparticles, or shopped fibres).

The construction of biocomposites can be classified depending on the shape of the material and the layout in the composite as well as the number of layers, single layer, or multi-layer, and finally, the orientation of the fibres in the different layers, Fig. 2.

3 Biodegradable Natural Fibrous Materials

Biodegradable composite is the combination of the biodegradability of the natural fibrous materials when combined with biodegradable polymers or natural resins to form a composite material.Several species of plants can produce fibres from its different parts, for instance from the stem: Jute, Flax, Ramie, Kenaf, leaves; from palm: Sisal, Banana, Abaca, or Cotton. Textile reinforcement for composites totalled $4.3 billion in 2018, with an annual average of 3.3% [5, 36]. Natural fibres are assortedas:

- **Cellulosic**.
  Seed: Cotton, Kapok.
  Stem: Flax, Hemp, Jute, Kenaf, Ramie.
  Leaf: Manella, Sisal, Banana, Abaca, Agave, Pineapple, Palm.
  Fruit: Coir.
  Wood: Hardwood, Softwood.
  Stalk: Rice, Wheat, Barley, Maize, Oat, Rye.
  Grass: Bamboo, Bagasse, Corn, Esparto, Canary, Rice.

- **Protein**.
  Hair: Wool, Alpaca, Camel, Cashmere.
  Secreted by the gland: Silk, Spider silk.

Bast fibres are environmentally friendly and can replace glass fibres in forming good biodegradable composites [3]. The world production of the bast fibres according

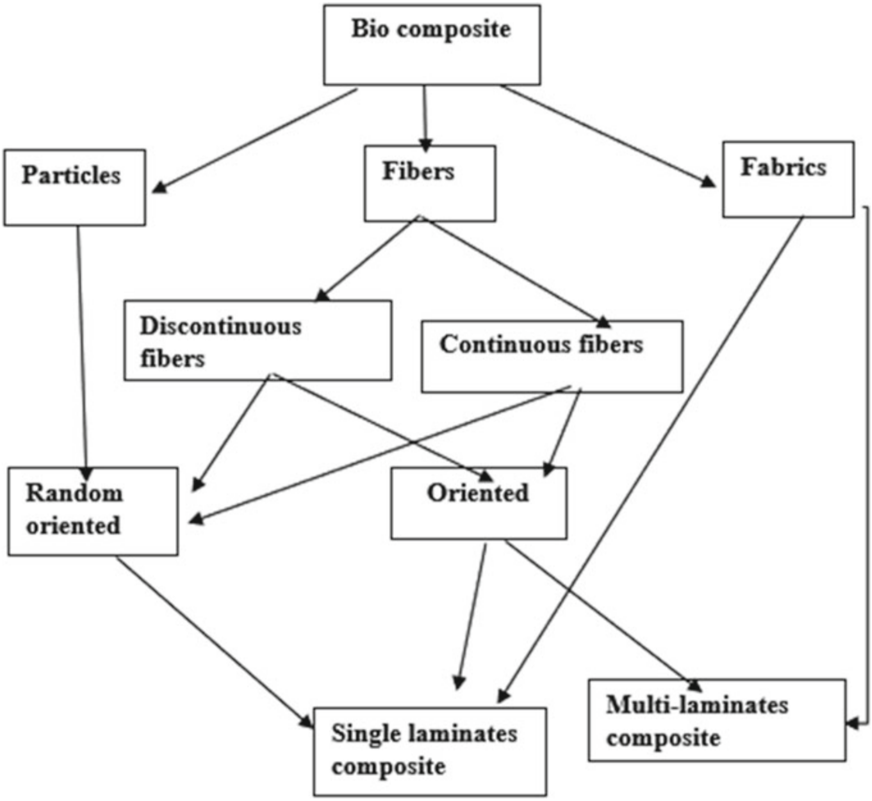
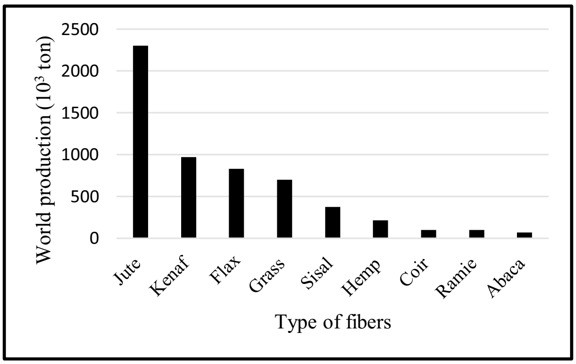


Fig. 2 Classification of biocomposites construction

to the different species is given in Fig. 3. Cotton fibres represent the highest production; it reaches 25 million tons while the bast fibres approximately 4 million tons [1, 29]. Bamboo fibres may reach 30 million tons [37].

Fig. 3 Bast fibres world production [by the author]



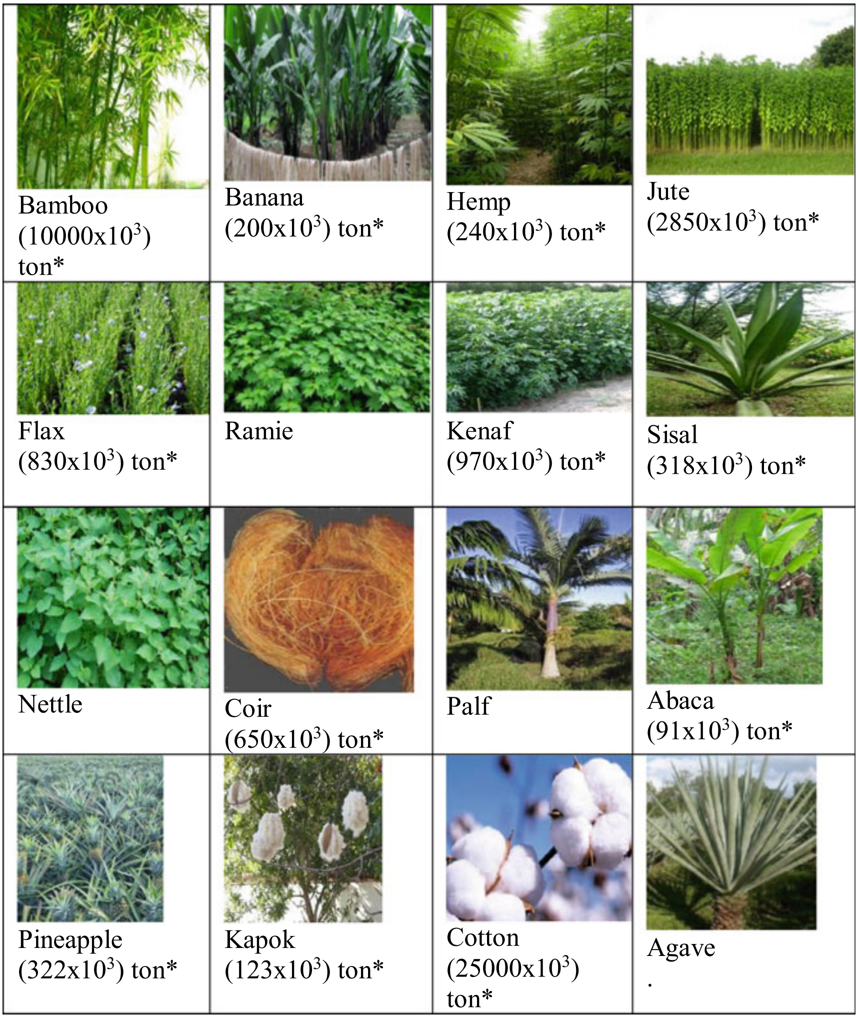


Fig. 4 Examples of different sources of natural biodegradable fibres [30–46]. * World annual production

Figure 4 shows examples of the different sources of natural biodegradable fibres [38–54].

3.1 *Biodegradable Fibres Properties*

Some Biodegradable fibres properties are provided in Table 2.

Table 3 provides the mechanical properties of the most used fibres for composite manufacturing, which vary greatly according to the source of the fibre's species and where it was cultivated.

Table 2 Fibres physical properties [3, 55–59]

Type of Fibre	Fibre length mm	Average fibre diameter mm	Density g/cm^3	Cellulose content %
Flax	33	0.019	1.45	75
Hemp	25	0.025	1.48	68.5
Jute	3.5	0.020	1.4	55
Kenaf	2–6	0.02	1.29	51
Ramie	160	0.06	1.48	73
Sisal	1–5	0.125	1.45	57
Banana	2.84	18.5	1.4	63
Pineapple	3–9	6	1.44	81
Abaca	6.0	0.02	1.5	60
Coir	200	0.48	1.1	30
Cotton	37	0.02	1.4	87.5
Bamboo	800	–	–	35
Soft wood	3.3	–	1.5	42.5
Hard wood	1–2	0.022	0.75	45

Table 3 Fibres mechanical properties [3, 55–59]

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Specific Young's modulus GPa/(g /cm^3)	Strain %
Flax	500	80	41	4.3
Hemp	550	45	30	3
Jute	625	37	27	2.5
Kenaf	550	25	24	2
Ramie	915	23	15	3.4
Sisal	450	15.5	10.5	8
Banana	720	30	22	2
Pineapple	1020	71	50	0.8
Abaca	700	13	9	6
Coir	140	6	5.2	1.1
Cotton	500	8	8.25	7
Oil Palm	330	150	2.7	2.2
Bamboo	575	27	18	3.1
Nettle	590	87	52.8	2.11
Coconut	150	30	27	5

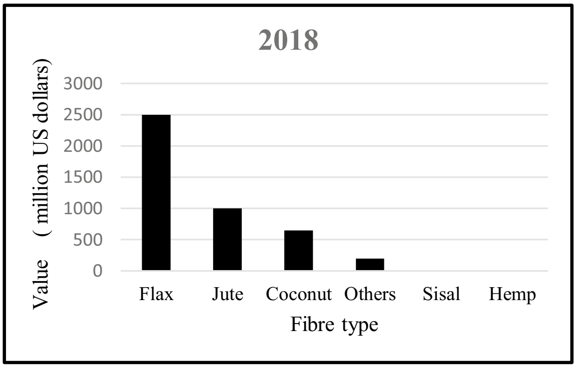


Fig. 5 Value of the world consumption from different natural fibres for manufacturing composite material [60]

The analysis of the different fibres world consumption (not included cotton) is illustrated in Fig. 5 which shows that flax fibres are most consumed.

4 Classification of Biodegradable Polymers

As has been mentioned, the polymer can be a natural material or synthetic, its molecular structure affects physical, mechanical, thermal, and other composite properties [3, 61]. The polymer properties are a result of the mechanical entanglement between chains and forces along with the molecules. Polymer's different properties and its structure define its end-use as well as the biodegradable properties of the biocomposites. The Biofibre composite materialscan be divided into fully biodegradable and partly biodegradable [62], depending on the biodegradability of the matrix that is capable of being decomposed by bacteria or other living organisms. Recently, several biodegradable matrixesare developed [63]. Polylactide acid (PLA), thermoplastic starch, cellulose esters, are examples of the biodegradable polymers from a natural source, while aliphatic polyester, aliphatic–aromatic polyester, polyvinyl alcohol, polyanhydrides, and polyethylene terephthalate are examples of biodegradable polymers from petroleum-based polymers [1]. Partly degradable composites are those using non-degradable polymers, such as polypropylene, polyester, or polyvinyl alcohol.

Natural biodegradable polymers are extracted from biomass or through organically modified organisms [62]. In the last decade, biodegradable polymers, especially PLA, are widely used in the manufacturing of NFPC and other industrial products [64]. Biodegradable polymers are classified:

Agro-polymer: Polysaccharides: starcheswheat, potatoes, maize, lignocellulosic products, wood, straws, chitin, chitosan, gums, alginates.

Bacterial polymers: Semi-synthetic polymers, polyhydroxyalkanoates, Poly (hydroxybutyrate-co-hydroxyvalerate). Microbial polyesters; Poly-3-hydroxyalcanoates, Poly (Hydroxybutyrate-Hydroxyvalerate), Poly (Hydroxybutyrate, Poly- ε-Caprolactones.

Polymers chemically synthesized: Polylactic Acid or Polylactide, Polyglycolic Acid.

In the selection of polymers for each application, some properties are essential for the compatibility of fibre properties, mechanical stresses applied on the composite during services, the suitability for the manufacturing technique of composite formation. The biodegradability of the composite can be tested according to international standards ASTM (D6400 or D6868) for duration of 90 days and up to 180 days, according to standard specifications for compostable plastics. Some other polymer properties are essential for compatibility with the end-use to fulfill matrix performance under various loading conditions, the manufacturing process requirements, and the life cycle analysis of the product.

The polymers can be either natural or synthetic, such as [3, 64]:

Natural

1. Polysaccharides

- Starch
- Cellulose
- Chitin
- Pullulan
- Levan
- Konjac

2. Proteins

- Protein from grains
- Collagen/gelatin
- Casein, albumin, fibrogen, silks, elastin

3. Polyesters

- Polyhydroxyalkanoates, copolymers

4. Other Polymers

- Lignin
- Shellac
- Natural rubber

Synthetic

1. Poly(amides).

2. Poly(anhydrides).

3. Poly(amide-enamines).

4. Poly(vinyl alcohol).

5. Poly(ethylene-co-vinyl alcohol).

6. Poly(vinyl acetate).

7. Polyesters.

- Poly(glycolic acid)
- Poly(lactic acid)
- Poly(caprolactone)
- Poly(orho esters)

8. Poly(ethylene oxide).

9. Poly(urethanes).

10. Poly(phosphazines).

11. Poly(acrylates).

A biodegradable polymer's chemical structure is given in Fig. 6. The biocomposites components can consist of biofibres and biopolymers.

5 Biocomposites

The biocomposites consist of two biodegradable components; biofibres and biopolymer as illustrated in Fig. 7.

Several combinations of fibres and polymers can be used for the manufacturing of the biocomposites as illustrated in Fig. 8. The choice of its components differsaccording to the composite end-use.

Fiber type, fiber volume fraction, water content, and matrix specifications determine the composite properties. The strength and modulus increase after a certain fiber volume fraction valueminimum,about 30% [3, 67–70]. Figure 8 shows some combinations of the biocomposites components.

Application of cellulose nanofibers increasesconsiderably on the account oftheirmechanical and degradability parameters [71].

6 Polymer Properties

The designer should be acquainted with the followingpolymer properties to assist in the selection of the suitable matrix for a certain application:

1. Intrinsic viscosity measurement
2. Density measurement

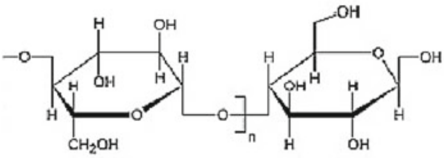
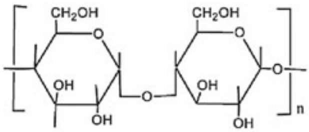
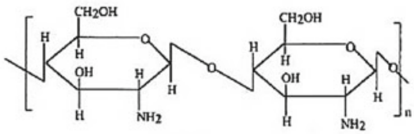
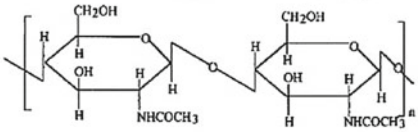
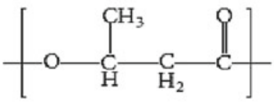
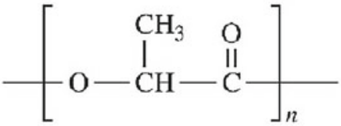
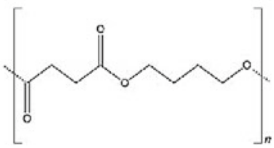
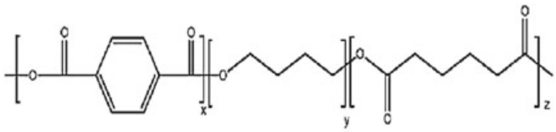
Polymer	Chemical structure
Cellulose	
Amylose	
Chitosan	
Chitin	
Polyhydroxybutyrate (PHB)	
Polylactic acid (PLA)	
Polybutylene succinate (PBS)	

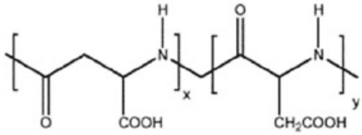
Fig. 6 Chemical structure of some biodegradable polymers [3]

3. Chemical family
4. Tensile properties
5. Flexural strength
6. Thermal—mechanical strength
7. Compression
8. Creep properties
9. Polymer physical properties

Aliphatic aromatic resin (HCR)



Thermal polyaspartate (TPA)



Carboxymethyl cellulose CMC

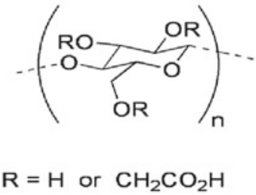


Fig. 6 (continued)

10. Identification of polymer additives
11. Adhesive properties
12. Aging testing for plastics and polymers
13. Chemical resistance testing
14. Environmental testing
15. Ballistic properties
16. Chromatography analysis of polymers
17. Mechanical properties of polymers
18. Mold shrinkage determination

6.1 Polymer Testing Methods

The polymers with different properties, such as the length of the polymer chain and chain structure, are used to form the matrix. There are thermoset and thermoplastic polymers [1]. When the thermoplastic polymer is heated, the de-bonding between chains occurs and the viscosity of the polymer increases, on the contrary to thermoset polymers—on heating of the polymer no movement between the molecules. The International standards used for polymer tests are given in Table 4.

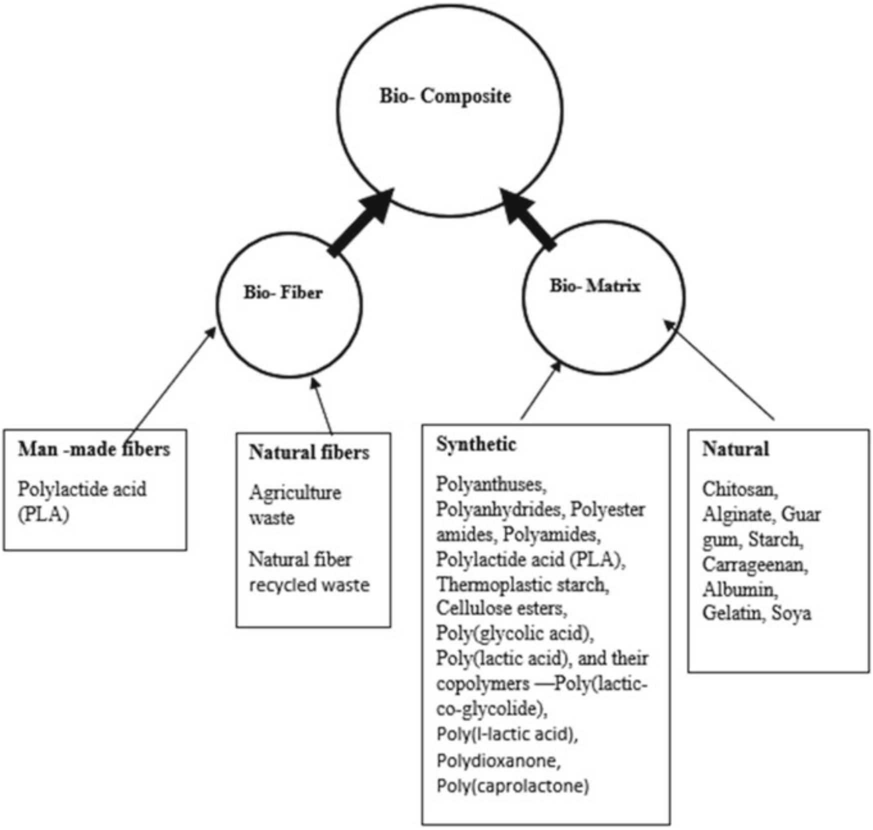


Fig. 7 Components of biocomposites

7 Biodegradation

Biodegradation is the ability of materials to break down to get disintegrated under the effect of the action of microorganisms, bacteria, fungi, enzymes, therefore thedeterioration of material structure [72, 73]. Choice of the type of fibre for biocomposites will mainly depend on its properties, suitability for end-use, and cost. The ideal life cycle of the biodegradable composite may be as given in Fig. 9.

As biodegradable materials, they must completely decompose within a short time after disposal—typically a year or less. Biodegradability of some materials is given in Table 5, which indicates that the biodegradable time of material depends on the surrounding media, and it may vary between few weeks to several years.

In some cases, such as in the case of nylon fabric, it needs 30–40 years for biodegradation time. Biodegradability processes pass through two phases [76].

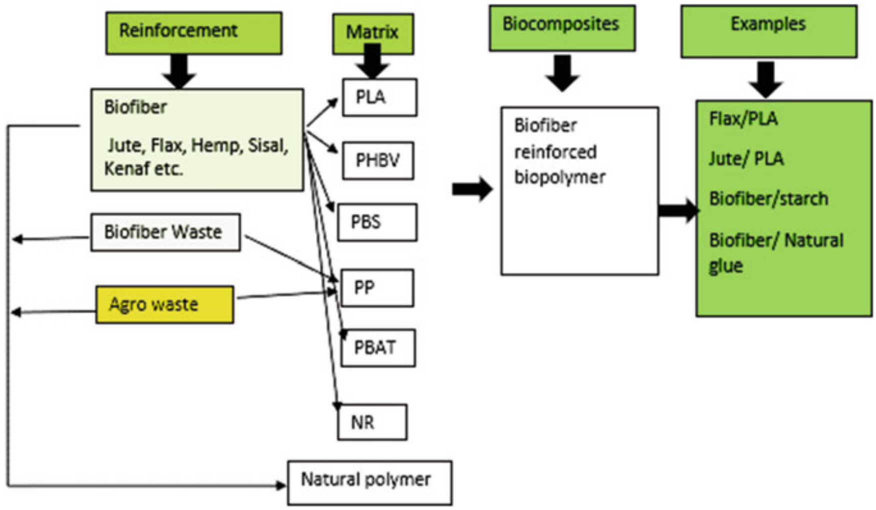


Fig. 8 Types of biocomposites

Table 4 Polymer testing methods

Test	ASTM number	Test	ASTM number
Intrinsic viscosity measurement	D4603	Creep	D7337
Density measurement	D792	Glass transition temperature (TG)	D7028
Tensile properties	D3039 D5083 D638 D638	Thermal expansion properties	D696
Chemical family	E1252 E168,	Deflection temperature under load	D648–01
Flexural strength	D7264	Moisture absorption	D5229
Thermal properties		Chemical resistance	
Compression	D6641 D3410 D695	Flammability	E2058–13a

1. Polymer undergoes significant weight loss, reduction in molecular weight, and fragmentation of soluble low molecular weight compounds.
2. Low molecular weight compounds degraded into CO2, water, and cell biomass (in aerobic conditions), and CH4, CO2, and cell biomass (in anaerobic conditions).

Biodegradability testing may be either aerobic (with oxygen available) or anaerobic (no oxygen available). The following equations indicate these two processes,

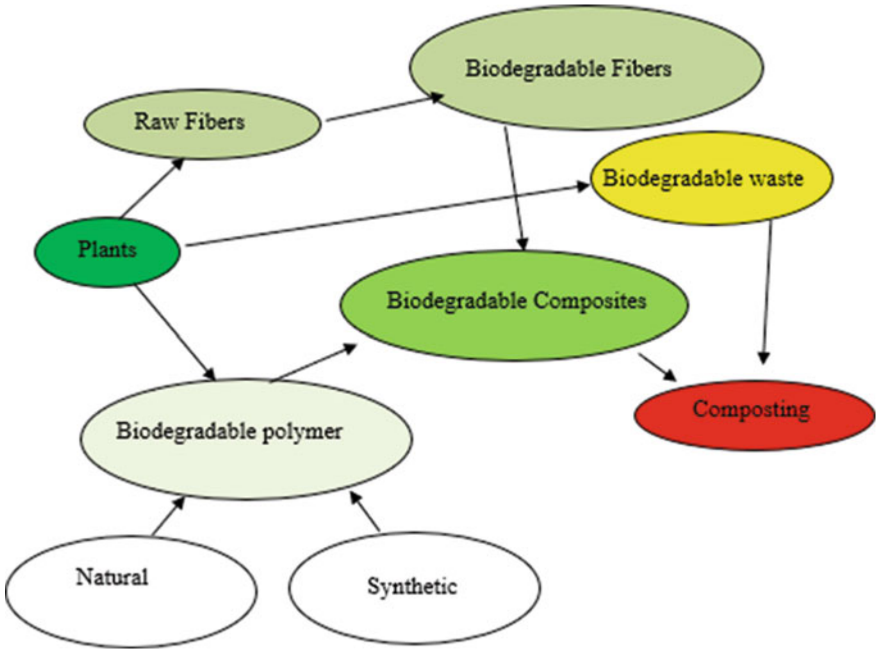


Fig. 9 Ideal life cycle of compostable, biodegradable composite

Table 5 Biodegradability of some materials [74, 75]

Material	Time (Terrestrial environment)	Material	Time (Marin environment)
Paper	Two to five months	Paper towel	Two to four weeks
Cotton T-shirt	Six months	Newspaper	Six weeks
Wool socks	One to five years	Cotton gloves	One to five months
Nylon fabric	Thirty to forty years	Wool gloves	One year
Plastic bags		Plywood	One to three years

where $C_{polymer}$ represents either a polymer or a fragment that is considered to be composed only of carbon, hydrogen, and oxygen [77].

- *Aerobic biodegradation.*
  $C_{polymer} + O_2CO_2 + H_2O + C_{residue} + C_{biomass} +$ Salts.
- *Anaerobic biodegradation.*
  $C_{polymer}\ CO_2 + CH_4 + H_2O + C_{residue} + C_{biomass} +$ Salts.

The biodegradation process is accomplished when the polymer is completely transformed into gaseous products and salts.

Table 6 Bacteria and enzymatic for degradation of polymers [81]

Bacteria	Enzymes	Polymer
Pseudomonas sp. E4	Alkane hydroxylase	LMWPE (Polyethylene)
P. putida AJ	Alkane hydroxylase	Vinyl Chloride (Polystyrene)
P. chlororaphis	Polyurethanase	Polyester, Poly urethane (PUR)
P. aeruginosa	Esterase	Polyester, Poly urethane (PUR)
P. protegens	BC2 12 Lipase	Polyester, Poly urethane (PUR)
P. fluorescen	Protease	Polyester, Poly urethane (PUR)
Pseudomonas sp.	Lipase	Polyethylene terephthalate PET
Pseudomonas sp. AKS2	Esterase	Polyethylene succinate PES
P. stutzeri	PEG dehydrogenase	Polyethylene glycol (PEG)
P. vesicularis PD	Esterase	Polyvinyl alcohol (PVA)
R. arrizus	Lipase	Polyethylene adipate (PEA), Poly butylenes succinate (PBS), and Polycaprolactone (PCL)
P. stutzeri	Serine	hydrolase Polyhydroxy alkanoate (PHA)
Tremetesversicolor	Laccase	Nylon, polyethylene (PE)
Rhodococcusequi	Aryl acylamidase	Polyethylene (PE), Polyurethane (PUR)

It was revealed that the biodegradability of the material depends on the microbial effect and is influenced by the availability of oxygen, temperature, and the availability of water in the surrounding environment. The aerobic degradation in the presence of air will convert into CO2 water and biomass. While in the absence of air it will be converted into CH4, CO2, traces of H2and H2S, and cell biomass [78, 79]. The degradation of the polymer differs according to its chemical structure. The CO2 production is accelerating at the beginning of the test till it reaches a plateau level as shown in Fig. 9. The time taken to reach the fixedvalueof CO2 development in the test was about 75–90 days [80]. Polymer with a high melting point is not expected to disintegrate. Factors, affecting microbial degradation, are moisture, potential hydrogen pH value, temperature [81, 82]. Table 6 gives the types of bacteria and enzymes used in the degradation of the different polymers [81].

8 Natural Fibre Biodegradations

The biodegradation of a material takes place in three steps: degradation, change in the properties of the material, digest of the material.The degradation rate of cellulose material not only depends on the presence of microorganisms and the availability of oxygen [76] but also the physical properties of natural fibres that, in its turn, are mainly determined by the chemical and physical composition. Growth of microorganisms is used in decomposition of substrate depends on several factors [83],and the

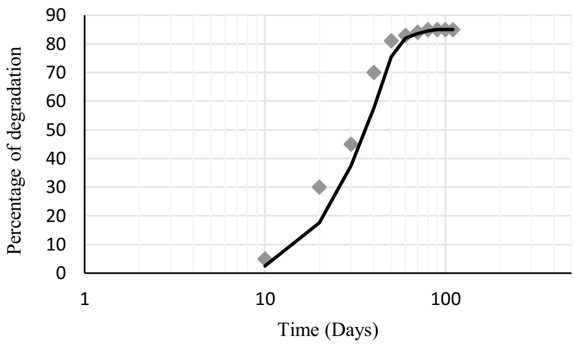


Fig. 10 Percentage of degradation versus time

addition the enzymes results in damaging the structure of the fibres. Biodegradation percentage is evaluated using the following expression:

$$= (\text{mg of } CO_2 \text{produced/mg of } CO_2 \text{ theoretical}) \times 100$$

Figure 10 shows the percentage of degradation as a function of time. The loss in weight of the sample starts at a high rate and slows down till it reaches a platform after 100 days.

In the case of the natural fibre (cotton, flax, jute, ramie) or regenerated fibres (viscose rayon, cellulose acetate), the fibre degradability depends on its internal structure, the degree of crystallinity, the cellulose percentage, and the fibre internal structure. The high crystallinity is the degradation rate [84]. Figure 11 shows the percentage of degradation of some fibres after 40 days [72].

Soil test, according to the ISO 11721- 1:2001 and ISO 11721:2003 standard] [85] for biodegradation of cellulosic fabric requires three months.It was revealed that jute and flax are more biodegraded than cotton. The weight loss of the sample after a degradation time of 3 months is shown in Table 7.

It was found that the degradation of the fibres starts at the surface and proceeds inside the fibre structure. The highly crystalline fibre structure will slow down its degradation [86].

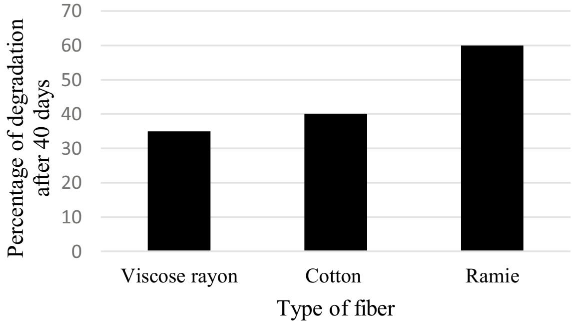


Fig. 11 Percentage degradation of fibres after 40 days [72]

Table 7 Weight loss of fibres after degradation time three months

Fibre type	Weight loss [%]	
	Hydrophilic	Hydrophobic
Cotton	38.69	40.97
Flax	30.27	28.08
Jute	38.79	41.94
Wool	33.16	14.92

9 Degradation of Biocomposites

The composite biodegradation depends on both fibre and polymer biodegradation. With the addition of natural fibre to the biodegradable polymer, the polymer properties and biodegradability of the resulting composites can be changed in comparison to the base polymer [76]. Crystalline structures of the polymer are responsible for the slow degradation of polymers. For example, use polypropylene as a matrix, the composite percent of degradation reaches 5% of that of natural fibre [80].From the experimental results of biodegradability, when using Polylactic acid (PLA) as a matrix for flax and rice husk, the addition of natural fibres slightly improves the biodegradability of Polylactic acid. Again, the use of Kenaf/Polylactic acid composite has a more significant effect on the biodegradation rate than in the case of rice husk/Polylactic acid composite [87]. Polymer biodegradability, standardized testing procedures may be carried out according to (ISO)or (ASTM) standards [88, 89].

Biodegradable composites offer great potential for achieving green, high-performance composites. However, PLA is degraded at a slow rate, ultimately staying at 33% at the end of the 100-day degradation [90, 91].

10 Methods for Determination of Biodegradation

The biocomposites have undergone remarkable improvements to be used for high-performance applications [76].Different standard methods have been applied to evaluate biodegradability as given in Table 8.

Test products are assessed for key chemical properties relating to the material's carbon content and then added to the method test chambers for analysis. Standards are measuring carbon dioxide (CO2) emissions or oxygen consumption under environmentally controlled conditions [92–95]. Biodegradation Testing for Compostable Solids includes ASTM D6400, ISO 16929, and ISO 14855. ASTM D6400 is most often used for composite and also as recommended composability method. The ISO standard organization has several other standards such as ISO 14855 and ISO 17556:2003.

Table 8 Standards for biodegradation determination

Standard No	Test duration	Standard No	Test duration
ASTM D5338	up to 180 days	ISO 9439	28 days
ASTM D5864	28 days	ISO 14593	28 days
ASTM D5988	6 months	ISO 14851	
ASTM D6400		ISO 14852	
BS 8472		ISO 14855	180 days
		ISO 17556:2003	28 days

11 Testing Methods for Natural Fibre/polymer Biocomposites Materials

11.1 Composite Materials Testing Methods

Generally, the mechanical testing of composite material includes:

1. Tensile strength
2. Compression
3. Flexure/bend strength
4. Puncture strength
5. Tear resistance
6. Peel strength
7. Shear strength
8. Delamination strength
9. Bond strength
10. Adhesion strength
11. Creep and stress relaxation
12. Crush resistance
13. Impact strength

12 Torsion

Depending on the application of the polymer and the composite end-use, the test should be chosen. Table 9 gives some basic tests and testing methods for characterization of composite properties that depend on the end-use to provide the required knowledge for a designer of a composite material.

Table 9 Composite testing

Test	ASTM	Test	ASTM
Moisture absorption	D570	Compressibility	D3410
Impact	D7136 / D7136M D3763 D 5628 D256 D1822	Density measurement	D1505-68, D 792
Fibre push-out test	STP1080	Compression	D 6641/ D 6641 M-01 D 695–96 D7137 D 3410
Fibre pull-out	D7332/D7332M	Shear	D5379 D7078 D3518 D3846 D5379
Three points flexural	D790	Fire calorimetry	E 1354
Tensile testing	D882 D5083 D3039 / D3039M	Flammability	D635
Adhesive strength	D 5379 D 5656		

13 Examples of Biofibre Composites Applications

Biocomposites have several new applications. Table 10 gives some examples of the biocomposites application.

In the straw fibre biocomposites different matrices can be used for example, with wheat straw it can be Wheat Gluten, Poly(3-Hydroxybutyrate-Co-Valerate), Natural Rubber, Polypropylene; for Wheat husks, Poly(Lactic Acid);for Rice husk, Poly(3hydroxybutyrate) and Poly(Lactic Acid);for Cornstalk, Natural Rubber, Poly(Lactic Acid); and for Corn husks, Polyethylene, Polypropylene [106–114].

13.1 Processing Methods of Biocomposites

The following is a list of technologies or approaches having implications for the increased use of natural fibres, Table 11. Film stacking, injection molding, and compression molding are the most widely used manufacturing methods.

Several factors affect biocomposites performance, such as processing method, fibre properties, fibre laying, fibre moisture, natural fibre assembly form (loose fibre,

Table 10 Examples of biofibre/polymer composites applications

Material	Composite	Applications	References
Wood raw wastes (WPC)	Wood/plastic and particle size of wood sawdust	Possibility of using waste raw materials for WPC products, like decking and railing systems,	[96]
Wood/natural fibre	Wood/natural fibre-plastic composites (WPCs)	Have great opportunities in residential and industrial sectors, oriented strand board, angles and lam-innated veneer lumber, wood I-joist, decking, railings, and window/door lineals, siding, roofing, and industrial decking	[97]
Straw fibre	Biocomposites with agricultural wastes	Bio-composite boards wheat straw fibres	[98–104]
Husk fibres	Husk fibre/ polymer Biocomposites	Sound absorber	[102, 103]

Table 11 Examples of Natural fibre/Polymer biocomposites and methods of manufacturing [3, 115, 116]

Reinforcement	Manufacturing Technology	Reinforcement	Manufacturing Technology
Non-woven fabrics	Molding under hydraulic pressing	Natural granulated fibres	Melting and composting in the twin-screw extruder
Natural fibres, non-woven	Extrusion molding, compression molding	Agriculture waste	Extrusion (single-screw) and compression molding
Fibers and bagasse blend	Fibre de-fibreized format formation	Fibres (jute, sisal, ramie) fabrics, or hybrids	Pultrusion
Fibres in roving or yarn forms	Extrusions with feeders of yarns	Natural fibres bundles, non-woven mats, bagasse	Concrete manufacturing technology
Non-woven	Resin transfer molding	Rice, sisal, jute, sugarcane bagasse, ramie residues	Sinterization at high temperatures

Table 12 Chemical structure of biodegradable polymers [3]

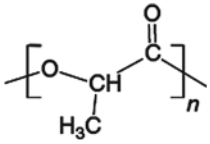
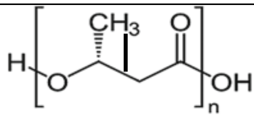
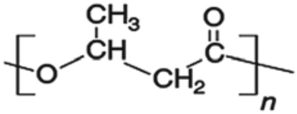
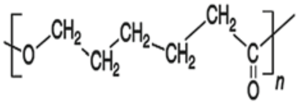
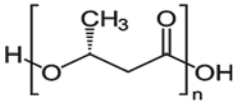
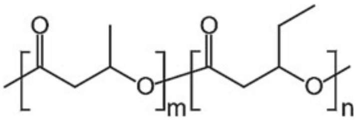
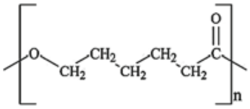
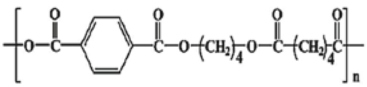
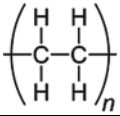
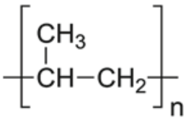
Polymer	Chemical structure
PLA: Poly(lactic acid)	
PHB: Polyhydroxybutyrate	
PHB: Poly(3-hydroxy butyrate) or	
PCL: Poly(ε-caprolactone)	
PHAs: Polyhydroxyalkanoates	
PHBV: Poly(hydroxybutyrate-co-hydroxyvalerate)	
PCL: Polycaprolactone	
PBAT: Poly(butylene adipate-co-terephthalate),	
PE: Polyethylene	
PP: Polypropylene	

Table 13 Examples of biocomposites constitutes [3, 10, 11, 24, 101, 109, 117–124]

Polymer	
Polypropylene **PP**	Flax, Coconut Husks, Hemp, Jute, Palm, Sisal, Sugarcane Bagasse, Wheat Straw
Poly(lactic acid) (**PLA**), Polycaprolactone (PCL) and Copolymers of PLA-PGA (PLGA)	Sugarcane Bagasse
Starch	Agricultural waste, Pseudo Stem
Soy protein	Sisal
Poly(lactic acid)	Flax, Hemp, Jute

yarns, woven, nonwoven, knitted fabric), composite structure (single laminate, multi-laminate), porosity, type of polymer and its properties. In the present time, biopolymers have been found an expanding application in the processing of biocomposites. The chemical structure of the biodegradable polymers is given in Table 12.

In the literature, several applications using biodegradable fibres or waste using different types of biopolymers were intensively investigated [3, 11]. Table 13 gives some application of biocomposites constitutes.

A new trend has arisen where two or more polymers are being selected as matrices for composite applications to get better results over individual biopolymers ones, such as PBAT/PBS blends [125].

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