Research Article

Natural Fiber-based Green Composites: Processing, Properties and Biomedical Applications

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Abstract

Since the advent of modern technological civilization, tremendous pollution has been emerged in our environment by disposing of waste material in the environment unconsciously. Some waste materials are biodegradable and some of them are non-biodegradable. Biodegradable waste, originated from plants or animals, can be decomposed by the natural organism (bacteria, fungi, etc.) and can be excluded from pollution. This degradation process may be rapid or slow but the environmental risks are low. On the other hand, non-biodegradable waste, obtained from inorganic components cannot be decomposed by the natural organism and act as a source of pollution. These wastes are being generated by humans, and every year billions tons of wastes are being dumped into the environment which puts our environment in danger. As a result, environmental consciousness has increased worldwide. This growing ecological and environmental awareness leads the world to develop eco-friendly materials. As the population grows day by day, it is not possible to reduce waste. So, it is wise to focus on developing new materials that would produce biodegradable waste. Recently, the attraction on the biocomposite (known as green composites) materials has significantly increased because it is generated from natural fiber which is biodegradable and it has the potential of being a substitute for conventional non-biodegradable products. Biocomposites are used in various industrial sectors, including the bio-medical industry. In this paper, the overall idea of natural fibers, extraction and surface modification methods of natural fiber, natural fiber-based biocomposites, fabrication and properties analysis of biocomposite, and recent applications of biocomposites in the medical sector have been reviewed. The primary incentive for developing and using biocomposite is to build a new generation of eco-friendly materials by replacing synthetic ones.

Keywords: Antibiotics, Biocomposites, Biomedical, Biosensor, Natural fiber, Tissue engineering

1 Introduction

According to "Worldometer" the world is now burdened with almost 7.9 billion people. And all of them are using different accessories and most of them are non-biodegradable. Some of them can be recycled and others cannot be recycled. Excessive usage of that material increased the environmental consciousness through the worldwide that leads the world to think and develop the new ecofriendly material like natural fiber-based polymers or biocomposites. Natural polymer or green polymer obtained from renewable sources are

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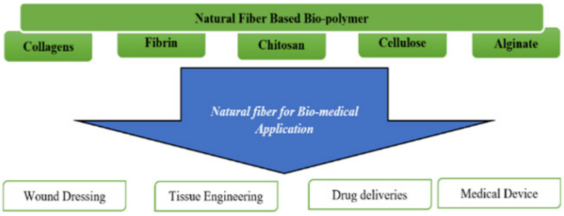


Figure 1: Schematic representation of Biomedical application done by natural fibers.

substitute for synthetic materials and their applications can decrease a huge amount of non-biodegradable waste. It is proved by several polymer industries which production are eco-friendly and sustainable [1]. The natural fibers accessibility, availabilityand low-cost in production have made biocomposites very appealing for numerous industrial applications like automobile, construction etc. natural fiber-based biocomposite are not only usable in the field of automotive, leisure industry, materials packaging, energy sector, sports, and construction but also usable in the field of biomedical applications such as wound healing, implants, biosensors, drug delivery, tissue engineering and medical devices etc. [2]. For example, biocomposite scaffolds are used in regenerative gene therapy [3], by developing bacterial cellulose composites with antibacterial properties to use it wound healing area, as dressings for contaminated wounds treatment [4], bio-templated silica synthesis in drug delivery, membrane technology and bio sensor [5], orthopedic, dental and various surgical operation etc. Figure 1 is the schematic diagram of bio-medical applications done by biocomposites which are obtained from natural fibers-based bio-polymers.

The reason of using natural fiber over synthetic fiber in bio-medical application is they are not only biodegradable but also bioresorbable. This characteristic helps in implantation, if any bio-material is implanted into body it is not required to be removed surgically [6]. Another big reason of using natural fiber-based bio-medical materials is reducing medical waste. Every year U.S hospitals produce almost 5.9 million tons of medical waste. A report "Health care waste, 2018" from WHO says the total amount of waste generated by health-care activities, about 85% is general, non-hazardous waste and remaining 15% is considered hazardous material that may be infectious, toxic or radioactive [7]. Another news "Can medical care exist without plastic?" By Sarah Gibbens, 2019; says 25% medical waste is plastic [8]. Natural fiber-based biocomposite material derived from renewable resources is an eco-friendly substitute for synthetic material like plastic because their applications in the bio-medical sector can reduce a huge number of non-biodegradable waste produced by the medical industry [9]. Environmental awareness has been increased now a days, [10], [11] as a result development of ecofriendly and environmentally sustainable materials have become an appealing and significant field of research. Improving natural fiber-based biocomposite materials obtained from renewable resources are eventually replacing synthetic fibers which is made from non-renewable petroleum-based resources [10], [11].

2 *Natural Fibers*

In this era, the significance and demand of natural fibers are increasing dramatically for their huge economic and environmental advantages like lightweight, biodegradability, less abrasive damage, abundant availability, good damping properties, less environmental footprint, high health safety, etc. Natural fibers are that kind of fibers which are directly obtained from natural resources like plant, animal and geological process. Based on this the natural fiber can be classified into three; Plant fiber (Found directly from different parts of the plant like bast, leaf, seed, fruit, etc.), Animal fiber (Animal hair like wool and silk fiber), Mineral fiber (Asbestos). The world now needs to develop some eco-friendly material and this need leads the whole world to the utilization of biodegradable composite material or Biocomposite material. Biocomposite materials are made from natural fiber. There is another fiber called Synthetic fibers which are man-made (Rayon, Nylon, acrylic, etc.). Current synthetic fibers are petroleum-based products and they are non-biodegradable. Compared with this synthetic fiber, natural fiber is a much better option for us. Table 1 shows the difference between natural fiber and synthetic fiber. Although Natural fibers have some issues. Natural fibers have higher moisture absorption properties because they have high cellulose content [12]. It can be solved by developing natural binders to hold the natural fiber in good shape. Natural fiber's mechanical properties are not as good as synthetic fibers and it can be developed by developing the poor dimensional, structural and

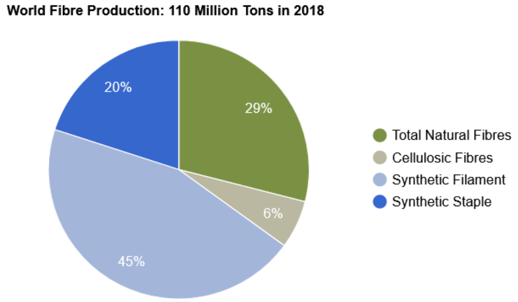


Figure 2: World fiber production 2018 [17].

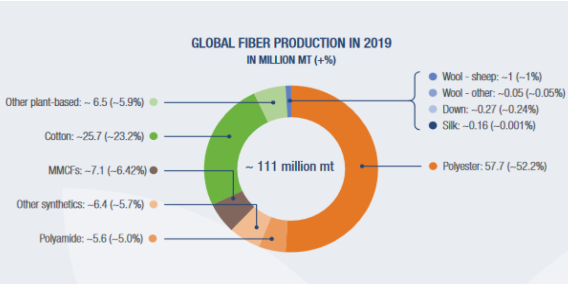


Figure 3: World fiber production 2019 [18].

environmental stability. One more major drawback of natural fiber is flammability because natural fibers have a lower decomposition temperature [13]. In this world, there is nothing without demerits. Natural fibers have also some drawbacks but those drawbacks are not things that cannot be solved. From the last two decades, enormous researches have been done to replace synthetic fibers by solving and developing natural fibers. Nowadays, considerable amounts of funds are being provided by our government and certain number of private funding agencies for ecofriendly and sustainable products [16]. The production of natural fiber is also increased day by day over the whole world. In 2018 the natural fiber production was 32 million metric tons where total fiber production was 110 million metric tons. Figure 2. Portraits the world fiber product in the year 2018 [17]. That means the natural fiber production was 29.09% of total fiber production. And in 2019 it was slightly increased and in Figure 3 it is presented [18].

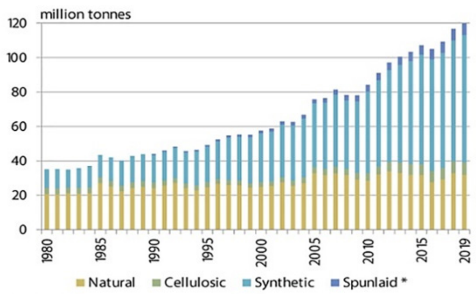


Figure 4: Global fiber production [19].

Global fiber production should be increased and especially, natural fiber. In Figure 4 the ultimate fiber production from 1980 to 2019 is shown from a report [19].

Total fiber production is increasing over the globe. And Production of natural fibers has also increased but is comparatively lower than that of synthetic fibers. So, for future betterment, the use and production of natural fiber should be increased.

Table 1: Difference between natural fiber and synthetic fiber [14], [15]

Criteria	Natural Fiber	Synthetic Fiber
Density	Low	High
Cost	Low	Double
Consumption of Energy	Low	High
Absorbent	Able to absorb heat, temperature, cold, sweat etc.	Not good absorbent.
Length	Naturally obtained	Controlled by man
Spinning	No spinning process is required	Melting, Wet or Dry spinning is required for filament production
CO_2	No	Yes
Biodegradability	Yes	No
Health risk	No	Yes
Recyclability	Yes	No
Ecofriendly	Yes	No

Figure 5: Dew retting process [22].

2.1 *Extraction of natural fibers*

There are several extraction methods or retting processes for natural fiber. It is dependent on the type of fibers and the required application of fiber which method is good for fiber extraction [20]. Retting is the method of extracting natural fiber from non-fibrous tissues. The quality, chemical composition, structure, and properties of the natural fiber depend on the retting method. In the retting process, two things are considered [21]:

1. Complete separation of fibers pectin materials.
2. To prevent over retting, termination of the retting process should be done at the correct time.

In the early age of extraction water and dew, retting was used to extract the natural fiber. But it is time-consuming processes because in these methods 14 to 28 days were required to extract natural fibers [20]. Nowadays various methods are introduced and they are:

2.1.1 Biological retting

It is a highly used and traditional method. Two types of biological retting and they are, dew retting and water retting.

2.1.1.1 Dew or field retting process

In this process, the harvested plants are thinly spread in the field and exposed to rain, sun, and dew like the Figure 5 [22]. until the fibers separate from stalk it takes 15–30 days to complete the whole process. During this time micro-organisms like fungi, aerobic bacteria attack the non-cellulose cell types and separate fiber bundles into smaller and individual fibers [23].

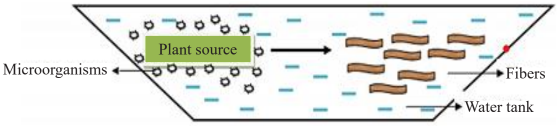


Figure 6: Water retting process [25].

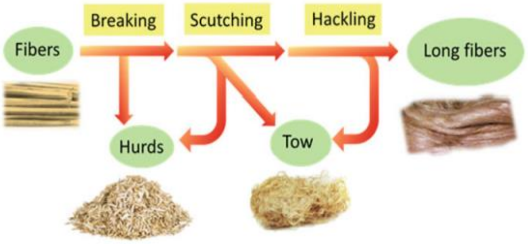


Figure 7: Schematic diagram of mechanical retting process [23].

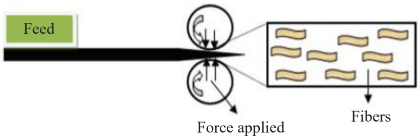


Figure 8: Mechanical retting process done by roller [25].

2.1.1.2 Water retting process

Though it is the most popular method of extraction, it produces low-quality fibers and is a time-consuming process [24]. Raw fiber is submerged in the water. The center parts of stems and external layer of harvested plants where the natural fiber belongs are penetrated by water. Microorganisms that present inside the natural fiber break down the cellular tissue, pectin, and various gums. In Figure 6 the water retting process is shown [25].

2.1.2 Mechanical retting

It generates high-quality fibers within a short time. Mechanical extraction consists of various steps like breaking, scutching, hackling. The schematic version of those steps is shown in Figure 7 [23]. These steps can be done in the traditional way or by mechanical decorticators like a hammer, roller, or beater; Figure 8 [25]. Repeated feeding of plant stem into the mechanical decorticators removes the gums and skin from the

Figure 9: Chemical retting process of sugar cane [29].

plants and natural fiber is extracted. After completing the process retted fibers are cleaned by water and then dried in sunlight [26].

2.1.3 Chemical retting

Also known as Surfactant retting. It is an extracting process where natural fiber is boiled with chemicals like soda ash, oxalic soda, and caustic soda [27]. It is popular because it produced high constant quality fiber without regarding the condition of weather. Various treatments are done by chemical retting like alkalization, oxidative degradation, bleaching treatment, acidic retting, etc. Among those most popular process for chemical retting is alkalization where sodium hydroxide (NaOH) is used as an aqueous solution to remove hemicellulose. The concentration of sodium hydroxide varies in the range of 1–25% by weight. The treatment is carried out at a warm temperature for about 2 h [23]. Then, the fibers are rinsed with distilled water in order to take away residual NaOH from fibers and then dried in the oven [28]. In Figure 9 chemical retting process by alkalization of sugar cane is shown because it is a promising raw material for the extraction of hemicelluloses.

2.1.4 Physical retting

Two technics are used in physical retting. One is stem blast where pressure and high temperature are used for separation and degradation of fiber. Another technic is ultrasound where partially squashed plant stems are dipped in a water tank where the water is mixed with alkalis and surfactants as pre-treatment of extreme ultrasound; it separates the fibers from the stem [21]. In the physically retting process, Plasma treatment, stem explosion, osmotic degumming, hydrothermal method, etc. are different types of physical retting method [23]. Plasma treatment is an useful method to modify the surface of fibers. Ablation, cross-linking, or surface activation can be caused by plama flow. Ablation is done by removing organic residues, Cross-linking occurs due to the interaction of radicals to the formation of covalent links and The surface energy is increased by surface activation [30]. The stem explosion is an autohydrolysis process where saturated stems are used. High pressure due to sudden decompression leads to the substantial breakdown of lignocellulose and defibrillation [23]. In the Hydrothermal process, water is taken at elevated temperature and pressure to degrade lignin and hemicellulose. It is applied in hemp and flax fiber already [31], [32]. Osmotic degumming treatment is applied in flax fiber. Due to the diffusive penetration of water inside the stem, hydrostatic pressure presses the epidermis. As a result, cracks occur at the epidermis and fibers are extracted [33], [34].

Figure 10: Enzymatic retting process. Flax stalk on shelf in retting/drying chamber (left) and ductwork within chamber (right) [37].

2.1.5 Enzymatic retting

It is also known as bioscouring. It produces fibers containing convenient properties. Enzyme retting employs a pectin corrupting process. By corrupting pectin, natural fiber is extracted from woody tissue [35]. Plant fibers are taken in tank water or bioreactor. Then different types of enzymes like pectinase, xylanases, etc. are directly added to the tank water to attack the gum and pectin material in the bast and extract fibers [36]. It is time-saving because its duration of retting is only 12–24 h, eco-friendly process. High energy and non-reusability of enzymes make the process cost-effective [36]. Enzymatic process is shown in Figure 10.

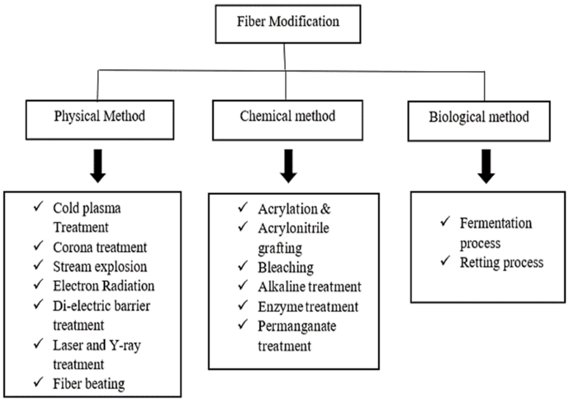


Figure 11: Methods of surface modification.

2.2 *Surface modification of natural fibers*

This eco-friendly natural fiber has been using since civilization as raw materials to meet the human need of daily life. Though low durability, high moisture absorption, wettability, inadequate adhesion with the matrix; but with the high-tech developments of industrial and environmental awareness; natural fiber has been replaced with synthetic fibers or reinforced biopolymer composites. That's why it is necessary to offer an improve treatment or modification of raw natural fiber to remove the drawbacks and achieve comparable proper surface bonding. Surface modification is mainly the process of modifying the surface of a material. It develops physical, chemical and biological characteristics that differ from the original raw materials of itself [38]. As a modification of surface properties is needed for its betterment, this depends on some following factors [39]:

- Fiber morphology
- composition of chemical
- Extractive chemicals and processing conditions
- Modification of plant fibers

However, some adjustment methods are followed to overcome those shortcomings for better performance. Those methods can be categorized initially into three basic techniques (Figure 11) and those techniques are used some more treatments for modification.

2.2.1 Physical method

Physical processes are done on natural fiber to discrete the fiber bundles into individual filaments and modify the surface characteristics for composite application with strong covalent bonds. Stretching, calendaring, rolling, dielectric barrier techniques , steam explosion treatment, corona treatment, cold treatment, laser, solvent extraction, and Y-ray treatment, thermo-treatment, electrical conduction, ionization, fiber beating- those are employed with physical methods [40]. Here cold plasma treatment introduces different functional groups that are able to build strong covalent bonds with matrix to increase surface energy and mechanical properties. This treatment has also some disadvantages too with highlighted benefits. No type of chemical composition changing is doing here.

Another process, corona treatment modifies the surface oxidation with two opposing electrodes where fiber is placed in the gap of electrodes based on low-frequency high speedy electrons [41], [42]. It is one kind of cost-effective low energy consumption process which is similar to the dielectric barrier discharge [DBD] process [43]. Though there need one or more dielectric barriers as an insulator in the DBD technique and has some disadvantages too.

2.2.2 Chemical method

The purpose of the chemical method is to make it less hydrophilic and defect-free with change the chemical composition of material by introducing new components to interact with the matrix [44]. Those most used treatments are- Alkaline treatment, Acrylation and acrylonitrile grafting, bleaching, isocyanate, maleated coupling, fatty acid derivates, triazine, silanization, benzoylation, use of peroxide, permanganate, enzyme treatment, and so on [21]. Alkaline treatment and Acylation-grafting are most significant among those for moisture absorption and swelling of natural fiber.

$$\text{Fiber–OH} + \text{NaOH} \rightarrow \text{Fiber} - \text{O} - \text{Na} + H_2O$$

This structure indicates a stage of Alkaline treatment in cellulose fiber modification by increasing surface roughness. Alkali treatment is used to remove the OH bond. It dissolves the amorphous constituents and to enrich the surface roughness with interfacial bonding of fiber-matrix [45].

$$\text{Fiber–OH} + CH_2 = CHCN \rightarrow \text{Fiber} - OCH_2CH_2CN$$

This is a reaction of acrylonitrile which is used in this process to modify fiber [46]. Acetylation is one important surface modification for plasticizing natural fibers and enhances dimensional stability of fiber-matrix. This treatment introduces rough surface topography with a strong mechanical interlocking matrix where belong a lower number of voids. The acrylation process is done by acrylic acid which reacts with cellulosic OH groups to promote moisture resistance properties [47]. A physicochemical treatment is also held for some natural fiber where describes degradation processes and molecular changes with the combination of chemical and physical treatment support. Improve separation of fiber bundles is the main purpose [48].

2.2.3 Biological method

Biological treatment involves microorganisms (bacteria, fungi) increased strength to enhance the establishment of a new generation of natural fiber composites with a refined matrix. Here, mainly used biomaterials in contact with biological processing for modifying the surface of the fiber. It is seen that deposition of about 5–6% nanosized bacterial cellulose, bacterial [Acetobacter xylinum] on the natural fiber surface resulted in improving adhesion to a renewable polymer [49]. It was also observed in a recent study, during the fermentation process of bacterial cellulose to generate improve fiber-matrix interface, cellulose nanofibrils are used on the surface of sisal and hemp fiber [49]. The fermentation processes, retting processes are commonly used here including the biological method for the growth of new generation. Retting treatment is one common treatment where bacteria and fungi are used to release enzymes by degrading pectic and hemicellulosic compounds [46]. Some selected surface modifications are given in Table 2.

3 Green Biocomposites

The growing world is now concerned about ecological and environmental issues. As a result, within this decade a tremendous improvement has been done in Green composite through the development of biocomposite. Composite is nothing but the mixing of two or more than two materials. When we are discussing biocomposite; it is a composite material that is biodegradable and provides minimal environmental impact at the end of its life cycle. The global market of composite is a multi-billion dollar business where grew by 6.3% in India, 2.1% in Europe in 2018 [56]. As it is eco-friendly and sustainable material so we are comfortable to call it green biocomposite. Biocomposite is formed by the combination of matrix or biodegradable resin and natural fibers. This matrix protects the fiber from environmental degradation and mechanical damage and this natural fiber is obtained from geological processes or directly found from natural resources like plants, animals. Based on the source biocomposite material can be classified into two sections (Figure 12) Non-wood/natural fiber and wood fiber. Non-wood fiber is more attractive than another one because of its properties and sustainability.

In wood fibers 60% of its composition is the wood element, thus it is called wood fiber. Softwood fibers are long and flexible, on the other hand, hardwood is shorter and stiffer.

Table 2: Some Selected surface modifications method

Natural Fiber	Surface Modification	Achievement	Reference
Cotton	Grafting fluorocarbon monomer	• Improve hydrophobicity	[50]
Hemp	Alkali treatment	• Tensile strength • Young's modulus • Thermal stability	[51]
Jute	Pyromellitic dianhydride grafting	• Absorption capacity	[52]
bamboo	Silane coupling agent	• Improve mechanical- thermal properties	[53]
Silk	Grafting of nano- Ag	• Antibacterial properties	[54]
Wool	Nano- ZrO_2	• Higher thermal stability	[55]

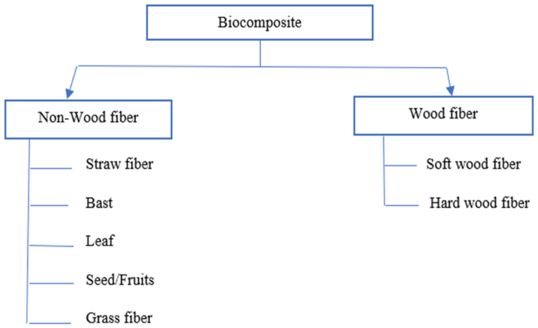


Figure 12: Classification of Biocomposite.

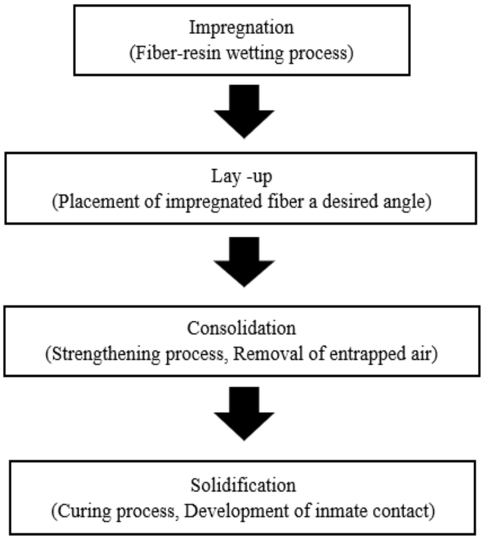


Figure 13: Schematic diagram of basic steps of fabrication process of biocomposite.

3.1 *Fabrication of biocomposites*

Fabrication is the process of manufacturing or inventing something. There are several fabrication processes of joining natural fiber and biodegradable polymer as the matrix. Generally, fabrication is done in four steps. Figure 13 is the schematic diagram of fabrication of biocomposite [57].

Design is the first concern of fabrication. It is a systematic way of creating products. Many factors play a vital role in designing new material and also in the fabrication process. So those factors should be considered. Summary of those factors [58], [59] are given below:

- Choice of materials
- Ease to manufacture
- Quantity to be manufactured
- Finishing quality
- Fitness for purpose
- Use of the product
- Durability
- Efficiency
- Running cost
- Ease to maintenance
- Safety
- Environmental and social considerations

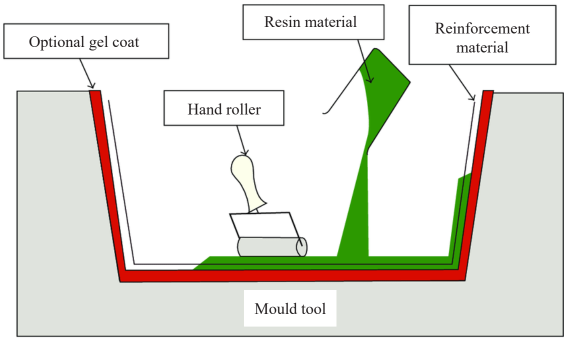


Figure 14: Hand lay-Up Process [62].

After completing the design manufacturing process; the main part of the fabrication will be started. The selection of manufacturing method among the several manufacturing methods depends on the type of polymer (thermoplastic or thermosetting) which are used as the matrix or bio-degradable resin for the development of biocomposite [60]. Some common manufacturing methods of biocomposites are:

3.1.1 Hand Lay-up process

In this fabrication process, natural fiber and matrix are mixed and placed into an open mold (Figure 14). Then mild pressure is applied by the roller. As a result, entrapped air will be removed. It has some advantages like no size constraints, low cost and some disadvantages like long curing time, air pockets and mild surface finisha, etc. [60], [61].

3.1.2 Pultrusion process

A continuous process for the manufacture of biocomposite with constant cross-section. Roving strands are pulled from a creel through a strand-tensioning device

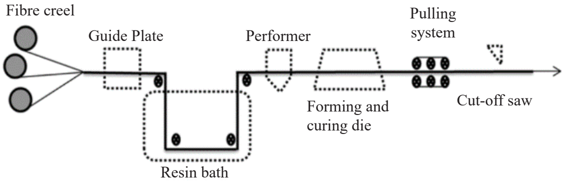


Figure 15: Schematic diagram Pultrusion process [65].

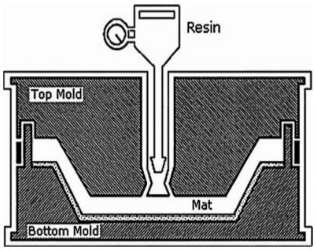


Figure 16: Resin Transfer Molding [67].

continuously into a resin bath. And then strands are passed through a heated die where curing occurs. The shape and size of the product depends on the cross-section of die. The pultrusion process for manufacturing biocomposite is shown in Figure 15. Some advantages of pultrusion are: overall low-cost production, good material usage, good rein quality, etc. On the other hand, disadvantages are: uniform cross Section, Excess resin(unintentionally) decrease the part strength, due to quick curing system strength may be decreased, etc. [63], [64].

3.1.3 Resin transfer molding process

Resin Transfer molding (RTM) is encompassed from Liquid composite molding process [66]. For good and smooth surface finishing, this process is utilized. Resin is injected into the mold through its cavity where fibers are laid. Then it is cured under pressure and heat. Illustrated view of RTM is given in Figure 16 [67]. Advantages are complex shaped product can be prepared, good surface finish, the filler can easily be added, high fiber volume, etc. Resin injection curing and heat transfer are the major limitations [64], [68].

3.1.4 Extrusion process

A device called spinneret is a corrosion-resistant metal plate containing a bunch of small holes. This process is done by forcing a thick and viscous liquid through the small holes of the spinneret to form continuous strings or filaments of semi-solid polymer. In the case of thermoplastic synthetic, this process is obtained by pressure and heat. Extrusion process is shown in Figure 17. There are 4 methods of spinning filaments and they are dry, wet, gel, and melt [67].

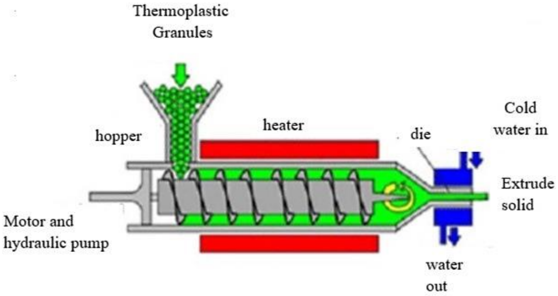


Figure 17: Extrusion process [69].

3.1.5 Injection process

This process is the most widely used method in industry for the production of biocomposite. Because it is simple and fast. The required amount of fiber and resin mixture is injected into the mold by an injection molding machine. This machine has three sections:

1) Injection unit: To melt, heat is delivered by this unit to the polymer matrix and then mix the polymer matrix with fiber. Then inject the melted mixture.

2) Mold: It is the closed mold having the shape of the final product which is made by the CNC machining process.

3) Ejection and clamping unit: Ejectors eject the final product when the whole injection process is completed.

The advantages of injection molding are high production rate, less curing time, etc. [67], [70].

3.2 ***Properties of biocomposites***

Biocomposites are discovered to replace the non-biodegradable waste that is harmful to our environment. But the story or replacement is not as good as we wanted and it is because of the properties. The stiffness, durability, and efficiency of non-biodegradable products like polythene, plastic, PVC, metal, etc. are much higher than these biocomposite or green materials. So now the world is concerned to increase the properties of biocomposite. The properties like mechanical, thermal, chemical properties should be discussed and our concern.

3.2.1 Mechanical properties

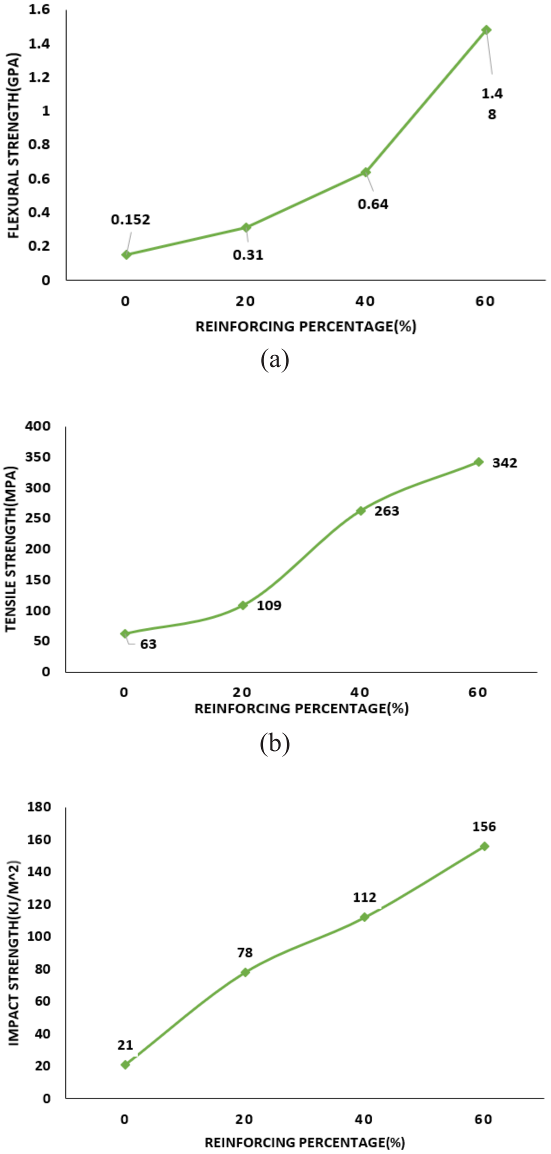
Mechanical properties of material indicate the physical properties that a material exhibits when force is applied to that material. For manufacturing of any instrument or machine or product, it is necessary to judge the mechanical properties of raw material and it is very crucial to classify or identify a suitable material for product manufacturing. In sense of mechanical, a material's properties should be detected from the following aspects [71].

- Material Stress and Strain
- Yield Strength
- Tensile Strength
- Toughness
- Hardness
- Brittleness
- Fatigue Strength

In biocomposite material, the fibers carry the structural load and the matrix keeps the structure in a solid phase. The mechanical properties of the final biocomposite material depend on different parameters like material properties, compatibility of natural fiber, and matrix used in the composition [72]. Brief summary from different studies [73], [74] done by some researchers based on mechanical properties of different natural fiber, used for biocomposite is given in the following Table 3.

Table 3: Mechanical properties of different natural fiber based biocomposite material [73], [74]

Fiber	**Tensile Strength (MPa)**	**Elongation at Break (%)**	**Young Modulus (GPa)**
Bast			
Flax	300–1500	1.3–10	24–80
Kenaf	295–1191	3.5	2.86
Jute	200–800	1.16–8	10–55
Hemp	310–900	1.6–6	30–70
Leaf			
Sisal	80–840	2–25	9–38
Pineapple	170–1627	2.4	60-82
Seed/Fruit fiber			
Cotton	264–800	3–8	5–12.6
Coir	106–175	14.21–49	4–6
Wood			
Hardwood	51–120.7		5.2–15.6
Softwood	45.5–11.7	4.4	3.6–14.3



(a)

(b)

(c)

Figure 18: Effect of reinforcing percentage of fiber on (a) Flexural strength, (b) Tensile strength, and (c) Impact strength [75].

A study [75] based on the improvement of mechanical properties of composite material says that reinforcing percentage of natural fiber can enhance the mechanical properties like flexural strength, tensile strength, impact strength, etc. These enhancements are shown in Figure 18.

3.2.2 Chemical properties

Chemical properties define the characteristics of the material and become evidence of a chemical reaction due to the surrounding environment. These properties are primarily dependent on the composition of the material. Biocomposite materials are formed with many organic compounds like cellulose, lignin, pectin, etc. which all of them are biodegradable, so it provides less impact on the environment. That is the reason for becoming Biocomposite as an eco-friendly material. In Table 4, the chemical composition of some Biocomposites are shown, found from some researches based studies [74].

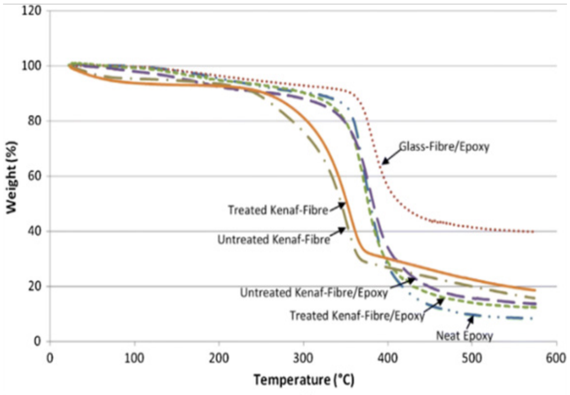


Figure 19: TGA curves of different natural fiber-based polymers and their composites [78].

3.2.3 Thermal properties

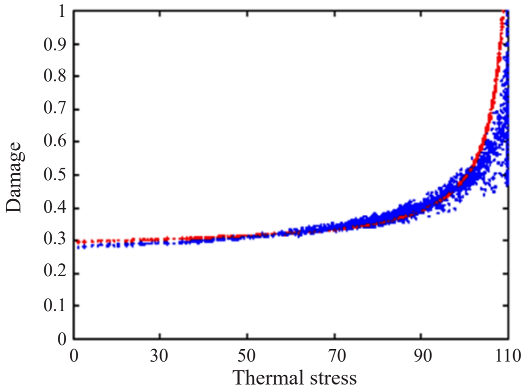
Heat capacity, thermal expansion, thermal conductivity, and thermal stress are known as Thermal properties. Actually, thermal properties of the material are those characteristics that are seen when the heat is passed through the material [76]. Thermal behavior depends on the chemical constituents of the material. The weight loss is increased with the increase of temperature simultaneously and here a graph related to these properties for kenaf fiber is shown in Figure 19. Surface modification can lessen the initial mass loss. At, the high temperature the thermal stability of natural fiber reinforced composite or biocomposite is more than natural fibers alone [77].

The coefficient of Thermal Expansion (CTE) correlates with volume fraction. The transverse CTE is increased but the longitudinal CTE is decreased with the rise of temperature [77].

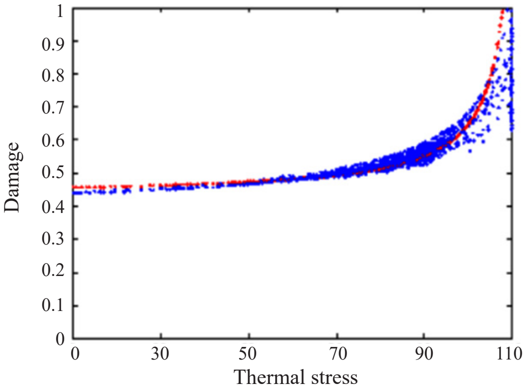
Thermal conductivity of polymer or biocomposite is significantly increased by adding thermally conductive fillers to a polymer matrix [79]. To enhance the conductivity, the matrix should be loaded with conductive filler like brass, aluminum fibers, carbon black, or graphite [80]–[85]. Thermal stress of biocomposite material is examined by providing different constraints in a research [86]. The research shows the interface

Table 4: Chemical composition of different natural fibers for biocomposite [74]

Fiber	Cellulose (wt%)	Hemi-cellulose (wt%)	Lignin (wt%)	Pectin (wt%)	Water Soluble (wt%)	Wax (wt%)	Micro-fibrillar Angle (deg)	Reference
Bast								
Flax	71–78	18.6–20.6	2.2	2.3	3.9–10.5	1.7	5–10	[40], [87], [88]
Kenaf	45–57	21.5	8–13	3-5	N.S.	N.S.	N.S.	[87]–[89]
Jute	61–71.5	13.6–20.4	12–13	0.2	1.2	0.5	8	[40], [87]
Hemp	70.2–74.4	17.9–22.4	3.7–5.7	0.9	2.10	0.8	2–6.2	[87], [88], [90]
Leaf								
Henequen	77.6	4–8	13.1	N.S.	N.S.	N.S.	N.S.	[89]
Pineapple	80–83	15–20	8–12	2–4	1–3	4–7	8–15	[88], [90]
Sisal	67–78	10–14	8–11	10	1.3	2	10–22	[40], [87]
Fruit/Seed fiber								
Cotton	85–90	5.70	0.7–1.6	0–1	1.0	0.6	20–30	[40], [87]
Coir	36–43	0.15–0.25	41–45	3–4	5.2–16.0	N.S.	30–49	[40], [87]
Wood								
Hardwood	43–47	25–35	16–24	N.S.	N.S.	N.S.	N.S.	[91]
Softwood	40–44	25–29	25–31	N.S.	N.S.	N.S.	N.S.	[91]



(a) σ = 105 N/m



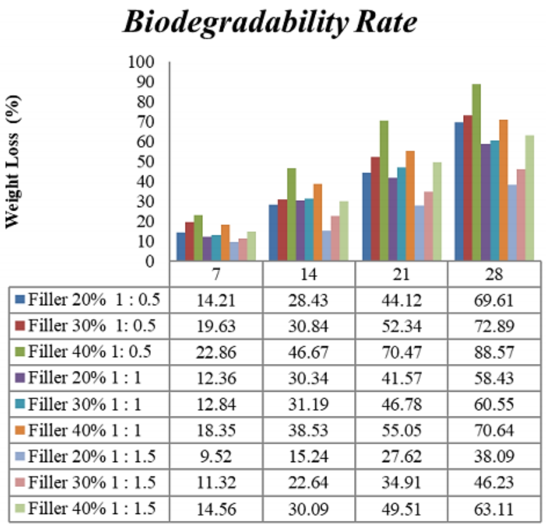
(b) σ = 125 N/m

Figure 20: The influence of the thermal stress on the interface damage [86].

damage function of thermal stress. When the thermal stress is increased, the damage increases. The level of damage is dependent on the constraints or material resistance. If the constraint (σ) is high then the initial level of damage will be high. For two types of constraint such as 105 N/m and 125 N/m the changes of thermal stress are presented in Figure 20(a) and (b) respectively.

3.2.4 Biodegradability

It is the ability of a material to decompose. Biodegradable materials mean materials that have the capacity of being biologically degraded by living micro-organisms. Again, microbial growth on biocomposite presents the biodegradation capability of the material. Lignin, a component of natural fibers resists microbial growth. So, less lignified natural fiber-based biocomposites are prone to microbial degradation [92]. Mechanical properties will be decreased with the degradation of biocomposites [93]. Because degradation creates holes and cracks over the whole part of biocomposite material. At the end of bio-degradation, bio-degradable materials will be complete breakdown and become part of the soil. When the material comes from nature, it will return to nature. That is why natural fiber-based biocomposites are bio-degradable. But how much time is needed for a biocomposite material? A leaf takes approximately one year for complete biodegradation, on the other hand, a large tree may take decades for the complete breakdown. So, the time for complete breakdown depends on the material itself. For example, wood polymer composites (WPCs) exhibit better properties than pure wood. Because in-situ WPC has the least biodegraded [94].



	7	14	21	28
■ Filler 20% 1 : 0.5	14.21	28.43	44.12	69.61
■ Filler 30% 1: 0.5	19.63	30.84	52.34	72.89
■ Filler 40% 1: 0.5	22.86	46.67	70.47	88.57
■ Filler 20% 1 : 1	12.36	30.34	41.57	58.43
■ Filler 30% 1 : 1	12.84	31.19	46.78	60.55
■ Filler 40% 1 : 1	18.35	38.53	55.05	70.64
■ Filler 20% 1 : 1.5	9.52	15.24	27.62	38.09
■ Filler 30% 1 : 1.5	11.32	22.64	34.91	46.23
■ Filler 40% 1 : 1.5	14.56	30.09	49.51	63.11

Figure 21: Biocomposite weight loss (%) against time (day) [95].

The level of biodegradability can be defined by weight loss. The test called the soil burial test indicates the biodegradability level. The biodegradability properties of biocomposite are affected by filler. More filler means more weight loss which means degradation will take less time. The addition of polypropylene may reduce weight loss. Figure 21 describes the biodegradability rate of Biocomposite. Biocomposite with 40% filler with 1:0.5 ratio of thermoplastic starch and polypropylene has the higher degradation rate or weight loss. It means biodegradability is high [95].

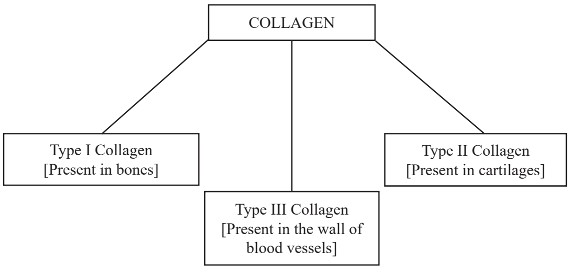


Figure 22: Classification of collagen.

4 Biomedical Applications of Biocomposites

Bio-medical is related to both medicine and science. It discusses the understanding, treatment, and prevention of diseases with applications of biological sciences, including biochemistry, molecular biology, and genetics [96]. Different types of biocomposites have already been used or are being researched for various medical treatments, with low-cost improvement, and for the rapid activating process. Doctors, Scientists, Researchers, suggesting biocomposite-related materials for fast restoring and healing function after injury or diseases.

4.1 *Biocomposites for tissue engineering*

Due to biocompatibility and biodegradability, those Biocomposites are used more in place of synthetic polymer composites in bone tissue engineering [97]–[101]. Alginate, Cellulose, Chitosan, Collagen, Gelatin, Fibrin; these natural biopolymers together made 'Hydroxyapatite', found in eggshell, fish scale, bovine bone, marine sources, etc. [102]. Those biopolymers can be hydrolytically or enzymatically degraded which derived from renewable resources [103].

4.1.1 Collagen-based biocomposites

Collagen, a fibrous protein is applied to form films, fibers, foams, bone, heart, nerve, and ligament in biomedicine [104]–[110]. Based on morphology collagen can be classified (Figure 22).

Collagen has many significant purposes which providing our skin structure and strengthening our bones. In our body it is the most abundant protein and major element of connective tissues. Compared to other albumin and gelatin-based natural polymers, Lipid-free intermolecular faces can be penetrated easily by collagen using its good surface-active protein [111]. By the combination of physical, chemical, and enzymatic treatment; cross-linking composites have been formed [111]–[115]. The chemical cross-linking methods are intermolecular and intramolecular covalent or ionic links between the amino acid residues of collagen. Scientists are founding new cross-linking components to improve the durability of collagen scaffolds using modern initiative techniques for bone tissue applications [116], [117].

4.1.2 Gelatin-based biocomposites

Gelatin is a translucent, colorless, flavorless biopolymer. It is derived from the collagen-reducing form that is initiated to cell adherence and migration of bone marrow cells taken from animal body parts. Different types of applications in pharmaceutical and medical science field, for following significant requirements [118], [119], such as

- Biocompatible
- Non-immunogenic
- Bioresorbable properties
- Dis-solution [45–50°C]

Gelatin completely dissolves at temperatures between 50°C and 60°C. As it is a water-stable bio component, dissolving in bi-functional reagents like acyl azides, carbo-diimides, glutaraldehyde, genipin, diisocyanate, and poly epoxy- compounds [120], Gelatin use as a treatment for joint and bone problems, such as osteoarthritis. It occurs when the cushioning cartilage between the joints breaks down, leads to pain and stiffness. However, epithelial cells, endothelial cells, osteoblasts fibroblasts, and glial cells -which support by specific gelatin-based biomaterial cell carriers [121], [122].

4.1.3 Chitosan-based biocomposites

Chitosan is an essential natural biopolymer. It is formed from the outer exoskeletons of crustacean animals such as lobsters, crabs and the cell wall of fungi. Being a linear polysaccharide chitosan is made of randomly distributed β-(1→4)-linked D -glucosamine (deacetylated unit) and N-acetyl- D -glucosamine (acetylated unit) [123], [124]. Due to their unique properties like mucoadhesion, non-toxicity, biocompatibility, hemostatic, antitumor, polycationic, antibacterial activity, capability to form a gel; they are widely used in several biomedical applications like tissue engineering, drug and gene engineering, wound healing, moreover.

4.1.4 Fibrin-based biocomposites

The action of the protease thrombin on fibrinogen causes to polymerize the fibrin which is a non-globular protein. A hemostatic plug is formed by this polymerized fibrin while the inner layerof a blood vessel is damaged, together with platelets. Not only a blood-clotting agent but also demeanors cell transplantation, angiogenesis, inflammation, hemostasis, and wound healing [125]. Fibrin is called 'a first responder' as it acts whenever our body is injured. The growth factors like fibroblast growth factor (FGF), enzymes (plasminogen), vitronectin, insulin-like growth factor-1, vascular endothelial growth factor (VEGF), and tissue plasminogen activator (tPA) responding to wound healing [126].

4.1.5 Cellulose-based biocomposites

Cellulose is an organic compound. A carbohydrate $(C_6H_{10}O_5)_n$-based source which is a polysaccharide containing a linear chain of several hundred to many thousands of β(1→4) linked glucose units. The cellulose-based biocomposite can be used in various biomedical application for its various convenient biomedical properties like low or no toxicity, biodegradability and biocompatibility with excellent biomechanical properties [127]. The biomedical applications of cellulose based biocomposite are given below in Figure 23.

Extracellularly produced bacterial cellulose (BC) from Agrobacterium, Alcaligenes, Acetobacter, Azotobacter, Gluconacetobacter, Rhizobium, Salmonella, and PseudomonasRhizobium, etc., has been applied in biomedical applications- using for artificial skin and blood vessels, wound healing scaffolds and hemostatic materials [128]–[130].

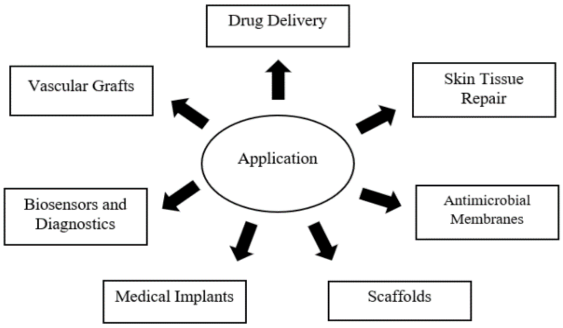


Figure 23: Biomedical Application of Cellulose-Nanofiber CNF.

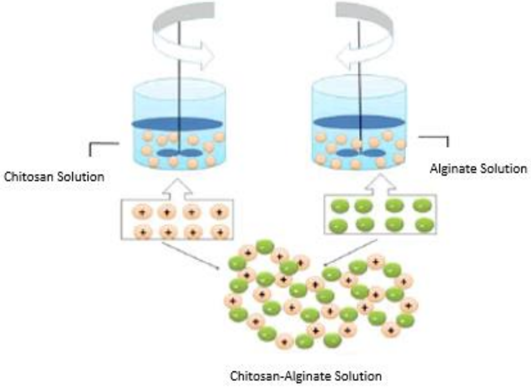


Figure 24: Formation of 3D microporous Chitosan-Alginate [133].

4.1.6 Alginate-based biocomposites

Alginate is extracted from brown algae and salt of alginic acid made of β-D-mannuronic acid and R-L-guluronic units. It is a natural polysaccharide. They are usually used as modified with cell adhesive peptides to promote cell adhesion to responses. Encapsulation and hemostatic dressings, scaffolds for tissue engineering, oral delivery, wounds healings- various biomedical applications. Alginate is also combined with other insoluble metallic salt-type materials to make desirable composites for biomedical use [131], [132]. In Figure 24, Alginate is mixed with Chitosan and create a scaffold.

4.2 *Biocomposites for wound dressing*

Wounds are identified as a breakdown in the continuity of any bodily tissue due to external violent action. It is caused by burns, trauma, and numerous skin disorders. Those wounds can distinct into two classes according to damage; open wounds and close wounds. Open wounds are always severe than close ones as the damaged tissues are exposed to the exterior. Moreover, abrasion, avulsion, incision, laceration, and puncture are five forms of wounds [134]. If the wound is left untreated, can spread an acute infection to the whole body. To stop spreading, the healing process needs to resist infections and stop the bleeding (hemostasis). Wound healing can be categorized into some stages [135].

- Stop the bleeding [hemostasis]
- Scabbing over [clotting]
- Rebuilding [growth and proliferative]
- Maturation [strengthening]

In this case, a preferable healing material can fully or partially recover its original set of properties by allowing gaseous permeationproviding a moist environment, and protect from bacterial infections [136]. Wound dressings have been widely used to facilitate wound healing by preventing bulk loss of tissue and bleeding. As biocomposites have unique features such as good hydrophilicity, biodegradability, permeability, biocompatibility, non-toxicity, non-immunogenic nature, and ease of surface modification, wound dressings have been developed in biomedical applications [137], [138].

A chitosan biocomposite film composed of bio-polymers like chitosan (CS) exhibiting as good antioxidant, anti-inflammatory properties to make an appropriate applicant for wound dressing. With certain qualities like as- porous sponges, cryo-gels, hydrogels, bandages, membranes, encapsulated; make that biopolymer-based chitosan as a better component in wound healing [139].

4.3 *Drug delivery*

Over the last few years, drug delivery has become an essential field of research and technology for the improvement of pharmaceutical properties of drugs, minimization of unnecessary side effects, and finding out superior clinical outcomes [140]. Drug delivery is a process that helps to transport a therapeutic agent from the site of administration to the targeted area or controlled release of therapeutic agents [141]. There are several ways of taken medicine; oral, topical, membrane, intravenous and inhalation are primarily some of them. Approaching any method, our main purpose is to deliver it into a targeted area of our body. In this case, the most effective use is nano biocomposites or bio composite-based polymers. Their potential advances are-

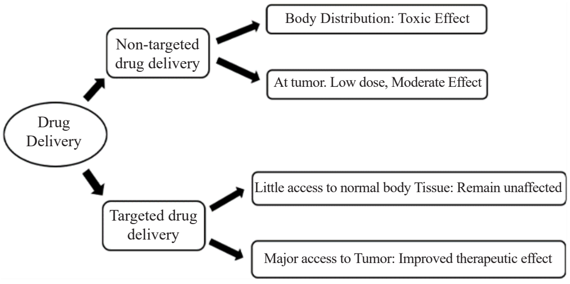


Figure 25: Flow diagram of drug delivery [143].

- As drug release rate depends on surface-bound release, erosion of nano-composite matrix, diffusion through a nano-composite matrix and combined release due to diffusion-erosion [142]; biocomposites are convenient due to biodegradation and biocompatibility.
- Incorporation and impregnation, those two methods are using in drug loading; where both methods are involved with nano- biocomposites [142], and incorporation is superior for some reasons than others.

Moreover, safe use, cost-effectiveness, eco-friendliness are advances of bio-based material. Nowadays, nano biocomposite-based drug distributors have become commercially available cheap. Figure 25 shows the concept of drug delivery in a body by a flow diagram.

4.3.1 TiAlV alloys

TiAlV alloy is made of 6% aluminum and 4% vanadium. It is an α+β alloy. With certain limitation, it is biocompatibile and highly corrosion resistant for orthopedic and the dental implant applications [144]–[147]. It is a new biocomposite coating material to inhibit postoperative complications. As Young's modulus of human bone is (approx. 25 GPa) where Young's modulus of TI6Al4V (mostly used TiAlV alloy) is (approx.110 GPa) which is comparatively larger [144], [148]. That's why it's not suitable for long-term protection. Despite releasing Al and V ions, for their high corrosion resistance, and biocompatibility properties; were used to prevent post-operative infection [145], [146], [149]. Ti6Al4V discs are chiefly coated with Poly-Lactic Acid (PLA), PLA-Hap, PLA-Gm-(Hap-Gm)- those three different sets of samples; to new drug delivery system which is shown in a paper [150]. Here sample was prepared of Ti6Al4V with

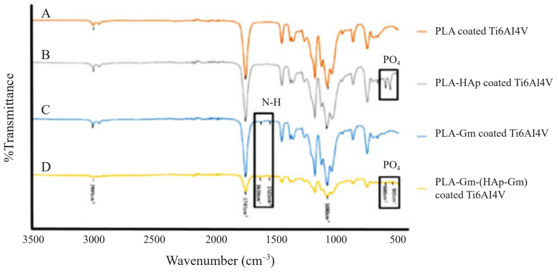


Figure 26: FT-IR results of all sets of PLA-biocomposite coated Ti6Al4V discs [150].

PLA biocomposites thin films and some characteristics observations and results were successfully received. In Figure 26, FT-IR spectra results have shown for different sets of PLA thin-film composites, where HAp characteristics peaks are major peaks for PLA-Hap coating sample on the other PLA-Gm-(HAp-Gm) coated samples are minor ones [151]–[154].

4.3.2 Alginate films

Alginate is extracted from natural brown algae which using among the most versatile bio-based polymer in drug delivery. In controlled drug delivery, Alginate-based biocomposite are always exclusive carriers [155]. Alginate is widely used in drug delivery because of its biodegradability, bioadhesive, and biocompatibility in pharmaceutical sciences. Alginate can be prepared through covalent cross-linking, emulsification, ionic gelation, polyelectrolyte complexation, spray drying, self-assembling, etc. for drug delivery. Due to their hydrophilic nature, Alginate films can defect moisture barriers. But by uniting G calcium ions crosslink with alginate, which can reduce the water vapor permeability of those films and produce more hydrophilic [156], [157]. Gelation is a difficult process that can be influenced by the various factor to impact the final properties of the film. Also, the alginate films containing diclofenac sodium act as a drug candidate. So, alginate-based biocomposite has been investigated for drug delivery, particularly in tissue repairing mechanisms. Small drug molecule can be released from the alginate gels and this releasing factor depends on the nature of the cross-linking agent and methods used for cross-linking [158]. Also dependent on the amount of the drug, the particle size of the drug, the type of formulation of the drug, the drug's solubility and its crystallinity. A study has observed that the levofloxacin formation in the chitosan-alginate hybrid gel for regulated release and effect of divalent alkaline ions (Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+}) [159].

4.4 *Biosensors*

By the definition of IUPAC, Biosensor is defined as – "A self-contained integrated device which is capable of providing specific quantitative or semi-quantitative analytical information using a biological recognition element which is in direct spatial contact with a transducer element" [160]. Biosensing refers to the detection of biomolecules using an analytical device with a physicochemical detector, detection of those contaminants such as microorganisms, biological species (DNA, RNA, proteins) with low concentrations of a desirable parameter [161]. So that this physicochemical analytical device is a biosensor that combines two sections; one is a sensitive biological element and the other is a detector meter transducer. There is various type of biosensors based on sensor device as well as biological materials. Electrochemical, Physical, piezoelectrical, thermometric, Optical, wearable, enzyme, DNA, immunosensors, magnetic, and so on. As biocomposites are versatile and so use as an effective transducing material for the construction of a wide range of biosensors such as enzyme sensors, genosensors, and immunosensors, etc. As biological bulk-modified materials, those biocomposites act not only as transducers but also as a reservoir for bio-materials [162]. This biosensor is based on a biocomposite that is biodegradable, homogeneous, and easily prepared. That biosensor exhibits rapid response with a linear calibration range within the short limit.

4.4.1 Cellulose Nanofiber (CNF) aerogel biosensor

With the development of nanotechnology, the ease of aerogel preparation has been completed throughout the years, although much remains to be done. Evaluation of aerogel has been observed day by day because the rate of population and industrialization is increasing. This 3D frame materials like bio-aerogels collaborate have some the challenges of low instability and sensitivity. To overcome these challenges this 3D frame materials are associated with 1D and 2D materials (Figure 21). This low-density nano-cellulose aerogel is used as a

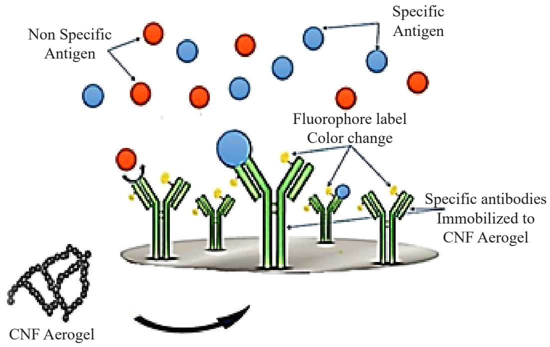


Figure 27: Schematic diagram of CNF aerogel in the diagnosis of specific antigens [165].

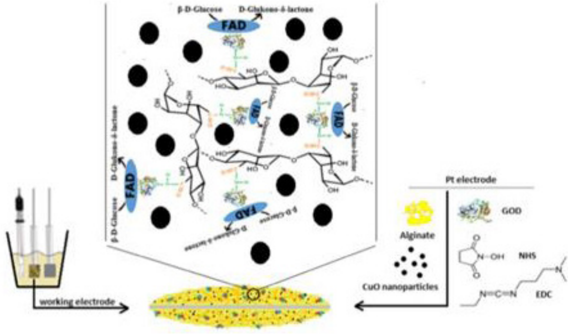


Figure 28: Biosensor construction of the Alginate-CuO-GOD electrode [167].

transducer biosensor surface. This matrix of bacterial CNF was used to fabricate hydrogen peroxide biosensors [163]. In 1931, Samuel Stephens Kistler discovered Aerogel which was used in an experiment in Stockton, California, USA. It was just a silica gel with sodium silicate (water glass) by heating in an autoclave at above critical temperature and pressure of gel [164]. Biocompatibility is a characteristic of material being able to initiate a host response, compatible with living tissue. After many studies and researches, that CNFs (Figure 27) were tested as excellent biocompatibility with no cytotoxicity and low toxicity.

4.4.2 Alginate copper oxide biocomposite for glucose biosensor

Mainly amperometric glucose biosensor based on glucose oxidase (GOD) and alginate -CuO nano-biocomposite film are used for cyclic voltammetry (CV), scanning electron microscopy (SEM), electrochemical impedance spectroscopy (EIS), etc.

Alginate is a gelatinous polysaccharide derive from brown algae which is a linear unbranched and pH shift copolymer with the features of hydrophilicity, low cost, non-toxicity, mild gelation conditions and biocompatibility[166].

In the fabrication of alginate-CuO-GOD (Figure 28) electrode in biosensing, after polishing the surface of the bare foil electrode is rinsed with ethanol. Then deionized in water and dried in air. 0.0002 g CuO and (1.5×10^{-4} g) alginate was added with acetate buffer mixture in an Eppendorf tube to get a homogeneous black dispersion. After doing some more experimental testing, To dry, the resulting alginate-CuO-GOD electrode is kept overnight at +4° [166].

In a study, it has been observed that Alginate-CuO-GOD nano-biocomposite is a noble biosensor for the detection of glucose and shows a good response to interference species such as phenylalanine, acetaminophen, ascorbic acid, and uric acid but less than glucose [167].

4.5 *Antibiotics*

From early civilization, natural fibers played a vital role in our society because these have been used to fulfill our daily based necessary things. Biocomposites have gained deep expertise in musculoskeletal infections. With the discovery of penicillin in 1929 and streptomycin in 1943, the journey of antibiotics has been started [168]. Antibiotics are chemical substances of antimicrobial produced by a living organism, active against certain targeted bacteria for fighting bacterial infections; they may either kill or inhibit the growth of bacteria. CERAMENT®G is an injectable, biodegradable antibiotic-loaded biocomposite that prevent against colonization of sensitive microorganisms, functions as an Osteoinduction and osteoconductive bone void filler comprised of calcium sulfate and hydroxyapatite. Therefore, eluding bactericidal concentrations and ensure local control of infections [169]–[171]. Development of biocomposite antimicrobial polymeric coating loaded with biodegradable nanoparticles are Chlorhexidine [$C_{22}H_{30}C_{l}2N_{10}$]; is a skin disinfectant and antiseptic used before surgery [172] and Rifampicin [$C_{43}H_{58}N_4O_{12}$]; which is used to treat several types of bacterial infections including tuberculosis [173]. A data-based study, suggest that local antibiotic therapy with an absorbable biocomposite can help achieve up to 90% cure rates in diabetics foot ulceration with osteomyelitis as able to achieve high local concentrations without systemic toxicity [174]. There are some more uses of biocomposite in the field of biomedical engineering Which are shown in Table 5.

5 Challenges and Issues

Besides the advantages of biocomposite, there are some issues and limitations. Some properties like biological resistance, thermal decomposition temperature, fire, moisture resistance, dimensional stability, ultra-violate, and ultra-violate, etc. of biocomposite are comparatively poor [183], [184]. Another problem is the long-term characteristics of biocomposite such as durability, lifetime prediction, creep and fatigue behaviors, etc. are still not discovered [185]. These problems limit the growth of the biocomposites application. To improve the problem of mechanical properties like impact strength, flexural strength, tensile strength, etc. by reinforcing more natural fibers arises another problems and they are water absorption tendency, undesirable odor, and ductility [90]. So, some more new processes should be introduced to improve the capability of natural fiber-based biocomposite without arising any other problems.

One more remarkable limiting factor for the use of biocomposites in the construction sector is the confined compatibility of natural fibers in heavy load-bearing, non-structural applications, and interior [20]. Not only in biocomposites but also natural fibers have some deficiencies. As the natural fiber is obtained directly from nature there is no control over its properties. Irregularity in the shape, size, and diameter of the natural fibers and their effect on the strength, hardness, and density of the biocomposite make some limitations on their applications as biocomposite [20]. After getting it from nature, natural fibers need to be extracted for further uses, but the process of extraction is a time-consuming operation. Poor protection to microbes, insects, and pests and high moisture responsiveness of natural fibers increase the probability of rotting, and eventually, an awful smell is released from those rotten fibers [186], [187]. To solve this problem anti-pests and anti-microbial coupling agents can be added with natural fiber to protect the fiber from pest infestation and microbial degradation, respectively [20]. Hydrophilicity; another significant resistance of natural fiber. For this hydrophilicity, at the interface and interfacial bonding of the biocomposites, poor coupling is seen that leads the biocomposite to function poorly [188], [189]. One more issue of natural fiber is unpredictable durability. Because of this problem natural fibers-based biocomposites face

Table 5: Examples of some cellulose and CNF-based biocomposites in biomedicine

Biocomposite	Advantages	Method	Application	Reference
✓ NFC ✓ Collagen composite aerogels	✓ Highly absorb ✓ Biocompatible	Cross-linked Di-aldehyde NCFs and collagen and formed aerogels	✓ Tissue engineering ✓ Wound dressing	[175]
✓ Super critically dried silica sol-gel	✓ Detected chemicals and organisms	Using viruses to trigger a response	✓ Biosensors ✓ Diagnostics	[176]
✓ Nano-cellulose (NA)	✓ Monitoring the level of protease	Complex of polypeptide-NA (PepNA)	✓ Biosensing	[177]
✓ NFC aerogel	✓ Drug release increasing significantly	NFC aerogel with the alkylating anti-neoplastic agent	✓ Cancer treatment	[178]
✓ Hydroxyapatite ✓ BC nano-composite	✓ Better adhesion ✓ Highly active ✓ Faster proliferated	Prepared HAp/BC nano-composite scaffolds	✓ Bone tissue engineering	[179]
✓ Cellulose-based hydrogel	✓ Superabsorbent capacity ✓ Satisfying biodegradability	Tested against E.coli	✓ Antibacterial activity	[180]
✓ Bacterial cellulose (BC) aerogel	✓ Equipped easily ✓ No aide interactions	BC aerogel matrix	✓ Drug delivery	[181]
✓ CNF aerogel	✓ Stretchable ✓ Sensitive	Generated cross-linking CNF surface with PSS in PEDOT	✓ Biosensing	[182]

major obstacles in both processing and application in different sectors [183].

There is nothing without any issues. So, overcoming these problems probably creates something even better. Natural fibers-based biocomposite may have some issues but those issues have been negligible when the advantages of natural fibers are discussed. But issues make some limitations on the applications of biocomposites. Therefore, the main challenge of using biocomposite is to overcome the limitations and issues of biocomposite.

6 Conclusions and Future Directions

In this paper, the overall idea of natural fiber and its composite material called natural fiber-based composites or biocomposites have been discussed with their production and modification methods. Their different kind of properties like mechanical properties, thermal properties, and chemical properties have been investigated. The usages of natural biopolymers for the synthesis and applications in biomedical engineering have been disclosed by considering its advantages and issues since the last century. Biocomposite materials are a comparatively new member of the composites class with preferable advantages like renewability, sustainability, and bio-degradable characteristics. The mechanical properties such as impact strength, flexural strength, tensile strength, ductility, elastic modulus, and durability of these biocomposites are increased markedly compared to the neat polymers from previous years. Although some critical issues arise. For example, moisture absorption, poor fiber/matrix adhesion, flammability, limited composite manufacturing conditions, hard fiber dispersion, limited composite manufacturing conditions, and fiber quality inconsistency. Thinking about future market opportunities, exploration of new natural fiber-based composites is important. Reinforcing multiple natural fibers can enhance certain mechanical properties. Their individual properties make biocomposites a promising future material for different industries, including biomedical. Bio-materials of different animal and plant-based models are using in tissue engineering, drug production, wound dressing, Bio-sensing, etc. Chitosan-based materials are being used in several pharmaceutical companies and they invest a huge amount of money for research and development of chitosan-based material because Chitosan-based nano-composite is in the infancy stage. Biocomposite materials have more economic opportunities in the field of automotive, civil engineering, sports, and agricultural sectors. It helps to reduce CO_2 emissions as compared to other sources. These individuality, advantages, huge opportunities in various fields help biocomposites to generate Green materials environment in the 21st century.

To ensure the usage of biocomposite material, the issues of biocomposites such as moisture absorption, flammability, low adhesion, poor thermal properties need to be solved. Furthermore, the undesirable and unpredictable major drawback is durability. Among all the studies regarding this durability of biocomposite, most of them are laboratory-based. The experimental study is recommended to develop this limiting factor of natural fiber base biocomposite in order to increase the future usage. Moreover, there are some less explored aspects of biocomposites like electric resistance, thermal conductivity, acoustic insulation, etc. To wider the application of biocomposites developing those less explored aspects is necessary. Depth analysis and research of different processing methods, surface modification techniques should be done. Hybridization, a method of combining natural fiber of different characteristics in order to get biocomposite with very good strength and excellent properties. Researchers should pay more attention to produce efficient and novel biocomposite products by using this convenient method in the near future. There are so many biocomposites such as chitosan-based nano-composites which are bio-degradable and advantageous but they are still in the infancy stage and are need to be more research and effort for being implemented in the biomedical sector. As well as for the future and long-term use of biocomposite in different sectors, new techniques to conduct long-term performance evaluation need to be upgraded and are essential to understand the outcome of environmental conditions in mechanical, thermal, and durability of composites. Many of the natural fibers can be mixed with non-biodegradable synthetic resins and produce new composite materials which are partially bio-degradable. The research and development of those types of composites should be continued in the future. Because Future research and development by exploring new materials and new areas application are need in order to replace the synthetic polymer composite.

References

[1] S. Ouajai and R. A. Shanks, "Preparation, structure and mechanical properties of all-hemp cellulose biocomposites," *Composites Science and Technology*, vol. 69, no. 13, pp. 2119–2126, Oct. 2009, doi: 10.1016/j.compscitech.2009.05.005.

[2] B. D. Ratner, "Biomaterials science: An interdisciplinary endeavor," in *Biomaterials Science*. San Diego: Academic Press, 1996, pp. 1–8.

[3] R. Li, T. Zeng, M. Wu, H. Zhang, and X. Hu, "Effects of esterification on the structural, physicochemical, and flocculation properties of dextran," *Carbohydrate Polymers*, vol. 174, pp. 1129–1137, Oct. 2017, doi: 10.1016/j.carbpol.2017.07.034.

[4] T. G. Volova, A. A. Shumilova, I. P. Shidlovskiy, E. D. Nikolaeva, A. G. Sukovatiy, A. D. Vasiliev, and E. I. Shishatskaya, "Antibacterial properties of films of cellulose composites with silver nanoparticles and antibiotics," *Polymer Testing*, vol. 65, pp. 54–68, Feb. 2018, doi: 10.1016/j.polymertesting.2017.10.023.

[5] K. Albert, X.-C. Huang, and H.-Y. Hsu, "Bio-templated silica composites for next-generation biomedical applications," *Advances in Colloid and Interface Science*, vol. 249, pp. 272–289, Nov. 2017, doi: 10.1016/j.cis.2017.04.011.

[6] G. S. Mann, L. P. Singh, and P. Kumar, "A peer review of the processing technologies and applications of green composites in a biomedical area," *International Journal of Technical Research & Science*, vol. 4, no. 6, pp. 13–19, Jun. 2019, doi: 10.30780/IJTRS.V04.I06.002.

[7] WHO, "Health-care waste," 2021. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/health-care-waste

[8] Nation Geographic, "Can medical care exist without plastic?," 2021. [Online]. Available: https://www.nationalgeographic.com/science/article/can-medical-care-exist-without-plastic

[9] R. Song, M. Murphy, C. Li, K. Ting, C. Soo, and Z. Zheng, "Current development of biodegradable polymeric materials for biomedical applications," *Drug Design Development and Therapy*, vol. 12, pp. 3117–3145, Sep. 2018, doi: 10.2147/DDDT.S165440.

[10] L. Mohammed, M. N. M. Ansari, G. Pua, M. Jawaid, and M. S. Islam, "A review on natural fiber reinforced polymer composite and its applications," *International Journal of Polymer Science*, vol. 2015, p. e243947, Oct. 2015, doi: 10.1155/2015/243947.

[11] S. K. Ramamoorthy, M. Skrifvars, and A. Persson, "A review of natural fibers used in biocomposites: Plant, animal and regenerated cellulose fibers," *Polymer Reviews*, vol. 55, no. 1, pp. 107–162, Jan. 2015, doi: 10.1080/15583724.2014.971124.

[12] M. E. Hoque, A. M. Khan, M. S. Islam, M. Asim, M. Jawaid, and O. A. Othman, "The effect of naturaldegradation on the mechanical and morphological properties of tropical woods," *Cellulose Chemistry and Technology*, vol. 50, no. 7–8, pp. 723–730, 2016.

[13] E. M. Taiwo, K. Yahya, and Z. Haron, "Potential of using natural fiber for building acoustic absorber: A review," *Journal of Physics: Conference Series*, vol. 1262, p. 012017, Aug. 2019, doi: 10.1088/1742-6596/1262/1/012017.

[14] Eduladder, "Difference between natural and synthetic fibres Science Ncert class 6," 2021. [Online]. Available: https://eduladder.com/viewquestions/10886/Difference-between-natural-and-synthetic-fibres---Science-Ncert-class-6

[15] P. Wambua, J. Ivens, and I. Verpoest, "Natural fibres: Can they replace glass in fibre reinforced plastics?," *Composites Science and Technology*, vol. 63, no. 9, pp. 1259–1264, Jul. 2003, doi: 10.1016/S0266-3538(03)00096-4.

[16] S. M. Rangappa, S. Siengchin, and H. N. Dhakal, "Green-composites: Ecofriendly and sustainability," *Applied Science and Engineering Progress*, vol. 13, no. 3, 2020, doi: 10.14416/jasep.2020.06.001.

[17] T. Townsend, "1B - World natural fibre production and employment," in *Handbook of Natural Fibres*. 2nd ed., Cambridge, UK: Woodhead Publishing, 2020, pp. 15–36.

[18] R. Luppino, "2020 Preferred Fiber and Materials Market Report (PFMR) Released!," 2021. [Online]. Available: https://textileexchange.org/2020-preferred-fiber-and-materials-market-report-pfmr-released/

[19] A. W. Engelhardt, "The Fiber Year 2020 – Deceleration along the textile chain," 2020.

[Online]. Available: https://fiberjournal.com/the-fiber-year-2020-deceleration-along-the-textile-chain/

[20] A. Vinod, M. R. Sanjay, S. Suchart, and P. Jyotishkumar, "Renewable and sustainable biobased materials: An assessment on biofibers, biofilms, biopolymers and biocomposites," *Journal of Cleaner Production*, vol. 258, p. 120978, Jun. 2020, doi: 10.1016/j.jclepro.2020.120978.

[21] S. A. N. Mohamed, E. S. Zainudin, S. M. Sapuan, M. D. Azaman, and A. M. T. Arifin, "1 - Introduction to natural fiber reinforced vinyl ester and vinyl polymer composites," in *Natural Fibre Reinforced Vinyl Ester and Vinyl Polymer Composites*. Cambridge, UK: Woodhead Publishing, 2018, pp. 1–25. doi: 10.1016/B978-0-08-102160-6.00001-9.

[22] LinenMe News, "Everything You Need to Know About Dew Retting Linen," 2020. [Online]. Available: https://www.linenme.com/news/everything-need-know-dew-retting-linen/

[23] L. Sisti, G. Totaro, M. Vannini, and A. Celli, "Retting process as a pretreatment of natural fibers for the development of polymer composites," in *Lignocellulosic Composite Materials*. New York: Springer International Publishing, 2018, pp. 97–135.

[24] C. Ngaowthong, M. Borůvka, L. Běhálek, P. Lenfeld, M. Švec, R. Dangtungee, S. Siengchin, S. M. Rangappa, and J. Parameswaranpillai, "Recycling of sisal fiber reinforced polypropylene and polylactic acid composites: Thermo-mechanical properties, morphology, and water absorption behavior," *Waste Management*, vol. 97, pp. 71–81, Sep. 2019, doi: 10.1016/j.wasman.2019.07.038.

[25] B. Aaliya, K. V. Sunooj, and M. Lackner, "Biopolymer composites: A review," *International Journal of Biobased Plastics*, vol. 3, no. 1, pp. 40–84, Jan. 2021, doi: 10.1080/24759651.2021.1881214.

[26] V. Sadrmanesh, Y. Chen, M. Rahman, and F. M. AL-Oqla, "Developing a decision making model to identify the most influential parameters affecting mechanical extraction of bast fibers," *Journal of Cleaner Production*, vol. 238, p. 117891, Nov. 2019, doi: 10.1016/j.jclepro.2019.117891.

[27] J. Patel and P. H. Parsania, "Characterization, testing, and reinforcing materials of biodegradable composites," in *Biodegradable and Biocompatible Polymer Composites*. Cambridge, UK: Woodhead Publishing, 2018.

[28] A. Oushabi, S. Sair, F. O. Hassani, Y. Abboud, O. Tanane, and A. E. Bouari, "The effect of alkali treatment on mechanical, morphological and thermal properties of date palm fibers (DPFs): Study of the interface of DPFePolyurethane composite," *South African Journal of Chemical Engineering (SAJCE)*, vol. 23, no. 1, pp. 116–123, Jan. 2017, doi: 10.1016/j.sajce.2017.04.005.

[29] Y. N. Solier, P. Mocchiutti, M. N. Cabrera, M. C. N. Saparrat, M. Á. Zanuttini, and M. C. Inalbon, "Alkali-peroxide treatment of sugar cane bagasse. Effect of chemical charges on the efficiency of xylan isolation and susceptibility of bagasse to saccharification," *Biomass Conversion and Biorefinery*, May 2020, doi: 10.1007/s13399-020-00776-0.

[30] A. A. Kafi, K. Magniez, and B. L. Fox, "A surface-property relationship of atmospheric plasma treated jute composites," *Composites Science and Technology*, vol. 71, no. 15, pp. 1692–1698, Oct. 2011, doi: 10.1016/j.compscitech.2011.07.011.

[31] A. Stamboulis, C. A. Baillie, S. K. Garkhail, H. G. H. van Melick, and T. Peijs, "Environmental durability of flax fibres and their composites based on polypropylene matrix," *Applied Composite Materials*, vol. 7, no. 5, pp. 273–294, Nov. 2000, doi: 10.1023/A:1026581922221.

[32] A. B. Thomsen, A. Thygesen, V. Bohn, K. V. Nielsen, B. Pallesen, and M. S. Jørgensen, "Effects of chemical–physical pre-treatment processes on hemp fibres for reinforcement of composites and for textiles," *Industrial Crops and Products*, vol. 24, no. 2, pp. 113–118, Sep. 2006, doi: 10.1016/j.indcrop.2005.10.003.

[33] R. Kozlowski, W. Koncewicz, J. Wojtysiak, and W. Podsiedlik, "Device for processing fibrous raw materials and the method of fibrous plants processing," 2013. [Online]. Available: https://patents.google.com/patent/EP2242876B1/ar

[34] W. Różańska and J. Wojtysiak, "The effect of physical factors on the process of physical-mechanical degumming of flax fibers," *Textile Research Journal*, vol. 85, pp. 391–403, Jan.

2014, doi: 10.1177/0040517514547214.

[35] R. M. Tajuddin and S. Aisyah, "Trends in natural fibre production and its future," in *5th Brunei International Conference on Engineering and Technology (BICET 2014)*, Jan. 2014, doi: 10.1049/cp.2014.1080.

[36] P. M. Tahir, A. Ahmed, S. SaifulAzry, and Z. Ahmed, "Retting process of some bast plant fibres and its effect on fibre quality: A review," *BioResources*, vol. 6, pp. 5260–5281, Nov. 2011.

[37] J. Foulk, D. Akin, R. Dodd, and D. Mcalister, "USDA Flax Fiber Pilot Plant," in *60th Flax Institute Proceedings*, Mar. 2004, pp. 1–12.

[38] M. Rahman, F. Zahin, M. A. S. R. Saadi, A. Sharif, and M. E. Hoque, "Surface modification of advanced and polymer nanocomposites," in *Environmental Nanotechnology*. New York: Springer International Publishing, 2018, pp. 187–209.

[39] K. F. Adekunle, "Surface treatments of natural fibres—A review: Part 1," *Open Journal of Polymer Chemistry*, vol. 5, no. 3, 2015, doi: 10.4236/ojpchem.2015.53005.

[40] K. G. Satyanarayana, G. G. C. Arizaga, and F. Wypych, "Biodegradable composites based on lignocellulosic fibers—An overview," *Progress in Polymer Science*, vol. 34, no. 9, pp. 982–1021, Sep. 2009, doi: 10.1016/j.progpolymsci.2008.12.002.

[41] N. Bahramian, M. Atai, and M. R. Naimi-Jamal, "Ultra-high-molecular-weight polyethylene fiber reinforced dental composites: Effect of fiber surface treatment on mechanical properties of the composites," *Dental Materials*, vol. 31, no. 9, Sep. 2015, doi: 10.1016/j.dental.2015.05.011.

[42] J. Peran and S. Ražić, "Application of atmospheric pressure plasma technology for textile surface modification," *Textile Research Journal*, vol. 90, p. 004051751988395, Oct. 2019, doi: 10.1177/0040517519883954.

[43] D. P. Ferreira, J. Cruz, and R. Fangueiro, "Chapter 1 - Surface modification of natural fibers in polymer composites," in *Green Composites for Automotive Applications*. Cambridge, UK: Woodhead Publishing, 2019, pp. 3–41.

[44] A. Valadez-Gonzalez, J. M. Cervantes-Uc, R. Olayo, and P. J. Herrera-Franco, "Chemical modification of henequén fibers with an organosilane coupling agent," *Composites Part B: Engineering*, vol. 30, no. 3, pp. 321–331, Apr. 1999, doi: 10.1016/S1359-8368(98)00055-9.

[45] S. M. Rangappa, S. Siengchin, J. Parameswaranpillai, M. Jawaid, C. I. Pruncu, and A. Khan, "A comprehensive review of techniques for natural fibers as reinforcement in composites: Preparation, processing and characterization," *Carbohydrate Polymers*, vol. 207, pp. 108–121, Mar. 2019, doi: 10.1016/j.carbpol.2018.11.083.

[46] M. Ravi, R. R. Dubey, A. Shome, S. Guha, and C. A. Kumar, "Effect of surface treatment on Natural fibers composite," *IOP Conference Series: Materials Science and Engineering*, vol. 376, p. 012053, Jun. 2018, doi: 10.1088/1757-899X/376/1/012053.

[47] M. M. Kabir, H. Wang, K. T. Lau, and F. Cardona, "Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview," *Composites Part B: Engineering*, vol. 43, no. 7, pp. 2883–2892, Oct. 2012, doi: 10.1016/j.compositesb.2012.04.053.

[48] P. Senthamaraikannan, S. S. Saravanakumar, M. R. Sanjay, M. Jawaid, and S. Siengchin, "Physico-chemical and thermal properties of untreated and treated Acacia planifrons bark fibers for composite reinforcement," *Materials Letters*, vol. 240, pp. 221–224, Apr. 2019, doi: 10.1016/j.matlet.2019.01.024.

[49] J. Cruz and R. Fangueiro, "Surface Modification of Natural Fibers: A Review," *Procedia Engineering*, vol. 155, pp. 285–288, Jan. 2016, doi: 10.1016/j.proeng.2016.08.030.

[50] M. P. Gashti, A. Pournaserani, H. Ehsani, and M. P. Gashti, "Surface oxidation of cellulose by ozone-gas in a vacuum cylinder to improve the functionality of fluoromonomer," *Vacuum*, vol. 91, pp. 7–13, May 2013, doi: 10.1016/j.vacuum.2012.10.015.

[51] G. W. Beckermann and K. L. Pickering, "Engineering and evaluation of hemp fibre reinforced polypropylene composites: Fibre treatment and matrix modification," *Composites Part A: Applied Science and Manufacturing*, vol. 39, no. 6, pp. 979–988, Jun. 2008, doi: 10.1016/j.compositesa.2008.03.010.

[52] D.-W. Gao, Q. Hu, H. Pan, J. Jiang, and P. Wang, "High-capacity adsorption of aniline using surface modification of lignocellulose-

biomass jute fibers," *Bioresource Technology*, vol. 193, pp. 507–512, Oct. 2015, doi: 10.1016/j.biortech.2015.06.138.

[53] T. Lu, M. Jiang, Z. Jiang, D. Hui, Z. Wang, and Z. Zhou, "Effect of surface modification of bamboo cellulose fibers on mechanical properties of cellulose/epoxy composites," *Composites Part B: Engineering*, vol. 51, pp. 28–34, Aug. 2013, doi: 10.1016/j.compositesb.2013.02.031.

[54] Z. Lu, J. Xiao, Y. Wang, and M. Meng, "In situ synthesis of silver nanoparticles uniformly distributed on polydopamine-coated silk fibers for antibacterial application," *Journal of Colloid and Interface Science*, vol. 452, pp. 8–14, Aug. 2015, doi: 10.1016/j.jcis.2015.04.015.

[55] M. P. Gashti and A. Almasian, "Citric acid/ZrO_2 nanocomposite inducing thermal barrier and self-cleaning properties on protein fibers," *Composites Part B: Engineering*, vol. 52, pp. 340–349, Sep. 2013, doi: 10.1016/j.compositesb.2013.04.037.

[56] M. Jawaid and S. Siengchin, "Hybrid composites: A versatile materials for future," *Applied Science and Engineering Progress*, vol. 12, no. 4, 2019, doi: 10.14416/j.asep.2019.09.002.

[57] R. J. Palmer and W. E. Moore, "Resin impregnation process for producing a resin-fiber composite," U.S. 5281388A, Jan. 25, 1994.

[58] M. Ashby and K. Johnson, *Materials and Design: The Art and Science of Material Selection in Product Design*. 3rd ed., Oxford, England: Butterworth-Heinemann, Jan. 2014.

[59] F. Dweiri and F. M. Al-Oqla, "Material selection using analytical hierarchy process," *International Journal of Computer Applications in Technology*, vol. 26, no. 4, pp. 182–189, Jan. 2006, doi: 10.1504/IJCAT.2006.010763.

[60] S. Mazumdar, *Composites Manufacturing: Materials, Product, and Process Engineering*. Florida: CRC Press, 2001.

[61] D. S. Cairns and J. D. Shramstad, "Evaluation of Hand Lay-Up and Resin Transfer Molding in Composite Wind Turbine Blade Manufacturing," U.S. Department of Energy, Tennessee, USA, Jun. 2000.

[62] S. Udupi and L. Rodrigues, "Detecting safety zone drill process parameters for uncoated HSS Twist Drill in machining GFRP composites by integrating wear rate and wear transition mapping," *Indian Journal of Materials Science*, vol. 2016, pp. 1–8, Jul. 2016, doi: 10.1155/2016/9380583.

[63] A. Fairuz, S. Sapuan, E. S. Zainudin, and C. Jaafar, "Polymer composite manufacturing using a pultrusion process: A review," *American Journal of Applied Sciences*, vol. 11, pp. 1798–1810, Oct. 2014, doi: 10.3844/ajassp.2014.1798.1810.

[64] J. K. Kim and K. Pal, *Recent Advances in the Processing of Wood-Plastic Composites*. Berlin, Germany: Springer Science & Business Media, 2010.

[65] M. R. Ketabchi, M. E. Hoque, and M. Khalid Siddiqui, "Critical concerns on manufacturing processes of natural fibre reinforced polymer composites," in *Manufacturing of Natural Fibre Reinforced Polymer Composites*. Berlin, Germany: Springer International Publishing, 2015, pp. 125–138.

[66] M. Arifur Rahman, F. Parvin, M. Hasan, and M. E. Hoque, "Introduction to manufacturing of natural fibre-reinforced polymer composites," in *Manufacturing of Natural Fibre Reinforced Polymer Composites*. Berlin, Germany: Springer International Publishing, 2015, pp. 17–43.

[67] F. M. AL-Oqla, A. Almagableh, and M. A. Omari, "Design and fabrication of green biocomposites," in *Green Biocomposites: Design and Applications*. Berlin, Germany: Springer International Publishing, 2017, pp. 45–67.

[68] I. Oliveira, S. Amico, J. Avila Souza, and A. Lima, "Resin transfer molding process: A numerical and experimental investigation," *International Journal of Multiphysics*, vol. 7, pp. 125–136, Jun. 2013, doi: 10.1260/1750-9548.7.2.125.

[69] A. Lotfi, H. Li, D. V. Dao, and G. Prusty, "Natural fiber–reinforced composites: A review on material, manufacturing, and machinability," *Journal of Thermoplastic Composite Materials (JTCM)*, vol. 34, p. 089270571984454, Apr. 2019, doi: 10.1177/0892705719844546.

[70] A. J. Kauffman, R. S. Black, and A. J. Stanley, "Apparatus for injection molding fiber-reinforced thermoset plastic articles," U.S. 4752201A, Jun. 21, 1988.

[71] Fractory, "Mechanical properties of materials," 2019. [Online]. Available: https://fractory.com/mechanical-properties-of-materials/

[72] Ş. Yildizhan, A. Çalik, M. Özcanli, and H. Serin, "Bio-composite materials: A short review of recent trends, mechanical and chemical properties, and applications," *European Mechanical Science (EMS)*, vol. 2, no. 3, Sep. 2018, doi: 10.26701/ems.369005.

[73] H. Cheung, M. Ho, K. Lau, F. Cardona, and D. Hui, "Natural fibre-reinforced composites for bioengineering and environmental engineering applications," *Composites Part B: Engineering*, vol. 40, no. 7, pp. 655–663, Oct. 2009, doi: 10.1016/j.compositesb.2009.04.014.

[74] T. Gurunathan, S. Mohanty, and S. K. Nayak, "A review of the recent developments in biocomposites based on natural fibres and their application perspectives," *Composites Part A: Applied Science and Manufacturing*, vol. 77, pp. 1–25, Oct. 2015, doi: 10.1016/j.compositesa.2015.06.007.

[75] A. I. Al-Mosawi, M. H. Al-Maamori, and Z. A. Wetwet, "Mechanical properties of composite material reinforcing by natural-synthetic fibers," vol. 3, no. 3, p. 6, 2012.

[76] BYJUS, "Thermal properties of materials - Physical properties of materials," 2021. [Online]. Available: https://byjus.com/physics/thermal-properties-of-materials/

[77] M. Asim, M. T. Paridah, M. Chandrasekar, R. M. Shahroze, M. Jawaid, M. Nasir, and R. Siakeng, "Thermal stability of natural fibers and their polymer composites," *Iranian Polymer Journal*, vol. 29, no. 7, pp. 625–648, Jul. 2020, doi: 10.1007/s13726-020-00824-6.

[78] N. Zulkarnain and B. Yousif, "Characteristics of kenaf fibre/epoxy composites subjected to thermal degradation," *Polymer Degradation and Stability*, vol. 98, pp. 2752–2759, Dec. 2013, doi: 10.1016/j.polymdegradstab.2013.10.008.

[79] M. Karkri, "4 - Thermal conductivity of biocomposite materials," in *Biopolymer Composites in Electronics*. Amsterdam, Netherlands: Elsevier, 2017, pp. 129–153. doi: 10.1016/B978-0-12-809261-3.00004-8.

[80] M. Aadmi, K. Mustapha, L. Ibos, and M. Hammouti, "Effective thermal conductivity of random two-phase composites," *Journal of Reinforced Plastics and Composites (JRP)*, vol. 33, Sep. 2013, doi: 10.1177/0731684413504018.

[81] Y. Agari and T. Uno, "Estimation on thermal conductivities of filled polymers," *Journal of Applied Polymer Science*, vol. 32, no. 7, pp. 5705–5712, 1986, doi: https://doi.org/10.1002/app.1986.070320702.

[82] F. Danes, B. Garnier, and T. Dupuis, "Predicting, measuring, and tailoring the transverse thermal conductivity of composites from polymer matrix and metal filler," *International Journal of Thermophysics*, vol. 24, no. 3, pp. 771–784, May 2003, doi: 10.1023/A:1024096401779.

[83] F. Danès, B. Garnier, T. Dupuis, P. Lerendu, and T.-P. Nguyen, "Non-uniformity of the filler concentration and of the transverse thermal and electrical conductivities of filled polymer plates," *Composites Science and Technology*, vol. 6, no. 65, pp. 945–951, 2005, doi: 10.1016/j.compscitech.2004.10.017.

[84] ProQuest, "Development and modeling of thermally conductive polymer /carbon composites," 2021. [Online]. Available: https://search.proquest.com/openview/fd69358fe7035a5c7028249945cafe4a/1?pq-origsite=gscholar&cbl=18750&diss=y

[85] J. M. Keith, C. D. Hingst, M. G. Miller, J. A. King, and R. A. Hauser, "Measuring and predicting in-plane thermal conductivity of carbon-filled nylon 6,6 polymer composites," *Polymer Composites*, vol. 27, no. 1, pp. 1–7, 2006, doi: https://doi.org/10.1002/pc.20160.

[86] S. Sadat, A. Mokaddem, B. Doumi, M. Berber, and A. Boutaous, "Investigation of the effect of thermal stress on the interface damage of hybrid biocomposite materials," *Mechanics and Mechanical Engineering*, vol. 23, no. 1, pp. 253–258, Jul. 2019, doi: 10.2478/mme-2019-0034.

[87] M. P. M. Dicker, P. F. Duckworth, A. B. Baker, G. Francois, M. K. Hazzard, and P. M. Weaver, "Green composites: A review of material attributes and complementary applications," *Composites Part A: Applied Science and Manufacturing*, vol. 56, pp. 280–289, Jan. 2014, doi: 10.1016/j.compositesa.2013.10.014.

[88] M. A. Fuqua, S. Huo, and C. A. Ulven, "Natural fiber reinforced composites," *Polymer Reviews*, vol. 52, no. 3, pp. 259–320, Jul. 2012, doi: 10.1080/15583724.2012.705409.

[89] X. Li, L. G. Tabil, and S. Panigrahi, "Chemical treatments of natural fiber for use in natural fiber-reinforced composites: A review," *Journal*

of Polymers and the Environment, vol. 15, no. 1, pp. 25–33, Jan. 2007, doi: 10.1007/s10924-006-0042-3.

[90] O. Faruk, A. K. Bledzki, H.-P. Fink, and M. Sain, “Biocomposites reinforced with natural fibers: 2000–2010,” *Progress in Polymer Science*, vol. 37, no. 11, Nov. 2012, doi: 10.1016/j.progpolymsci.2012.04.003.

[91] M. Jawaid and H. P. S. A. Khalil, “Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review,” *Carbohydrate Polymers*, vol. 86, no. 1, pp. 1–18, Aug. 2011, doi: 10.1016/j.carbpol.2011.04.043.

[92] E. Bari, J. Morrell, and A. Sistani, “Durability of natural/synthetic/biomass fiber-based polymeric composites: laboratory and field tests,” *Composites Science and Engineering*, pp. 15–26., 2019, doi: 10.1016/B978-0-08-102290-0.00002-7.

[93] V. A. Alvarez, R. A. Ruseckaite, and A. Vázquez, “Degradation of sisal fibre/Mater Bi-Y biocomposites buried in soil,” *Polymer Degradation and Stability*, vol. 91, no. 12, pp. 3156–3162.

[94] M. Enamul Hoque, M. A. M. Aminudin, M. Jawaid, M. S. Islam, N. Saba, and M. T. Paridah, “Physical, mechanical, and biodegradable properties of meranti wood polymer composites,” *Materials & Design*, vol. 64, pp. 743–749, Dec. 2014, doi: 10.1016/j.matdes.2014.08.024.

[95] D. R, S. N, Zulnazri, and R. M, “Mechanical and biodegradability properties of bio composite from Sago starch and straw filler,” *Eurasian Journal of Analytical Chemistry*, vol. 13, no. 6, pp. 244–248, Dec. 2018.

[96] H. M. H. P. Company, “The american heritage dictionary entry,” 2021. [Online]. Available: https://www.ahdictionary.com/

[97] B. Ben-Nissan, “Natural bioceramics: From coral to bone and beyond,” *Current Opinion in Solid State & Materials Science*, vol. 7, no. 4, Art. no. 4, Aug. 2003, doi: 10.1016/j.cossms.2003.10.001.

[98] S. A. Clarke and P. Walsh, “12 - Marine organisms for bone repair and regeneration,” in *Bone Substitute Biomaterials*. Cambridge, UK: Woodhead Publishing, 2014, pp. 294–318. doi: 10.1533/9780857099037.3.294.

[99] M. L. Hans and A. M. Lowman, “Biodegradable nanoparticles for drug delivery and targeting,” *Current Opinion in Solid State & Materials Science*, vol. 6, no. 4, Aug. 2002, doi: 10.1016/S1359-0286(02)00117-1.

[100] X.-J. Ji, L. Gao, J. Liu, R. Jiang, F. Sun, L.-Y. Cui, S.-Q. Li, K. Zhi, R. Zeng, and Z.-L. Wang, “Corrosion resistance and antibacterial activity of hydroxyapatite coating induced by ciprofloxacin-loaded polymeric multilayers on magnesium alloy,” *Progress in Organic Coatings*, vol. 135, pp. 465–474, Oct. 2019, doi: 10.1016/j.porgcoat.2019.06.048.

[101] K. Y. Lee and S. H. Yuk, “Polymeric protein delivery systems,” *Progress in Polymer Science*, vol. 32, no. 7, Jul. 2007, doi: 10.1016/j.progpolymsci.2007.04.001.

[102] J. A. Lett, S. Sagadevan, I. Fatimah, M. E. Hoque, Y. Lokanathan, E. Léonard, S. F. Alshahateet, R. Schirhagl, and W. C. Oh, “Recent advances in natural polymer-based hydroxyapatite scaffolds: Properties and applications,” *European Polymer Journal*, vol. 148, p. 110360, Apr. 2021, doi: 10.1016/j.eurpolymj.2021.110360.

[103] S. M. K. Thiagamani, S. Krishnasamy, and S. Siengchin, “Challenges of biodegradable polymers: An environmental perspective,” *Applied Science and Engineering Progress*, Mar. 2019, doi: 10.14416/j.asep.2019.03.002.

[104] O. Karadas, D. Yucel, H. Kenar, G. Kose, and V. Hasirci, “Collagen scaffolds with in situ-grown calcium phosphate for osteogenic differentiation of Wharton’s jelly and menstrual blood stem cells,” *Journal of Tissue Engineering and Regenerative Medicine*, vol. 8, Jun. 2012, doi: 10.1002/term.1555.

[105] E. Kijeńska, M. P. Prabhakaran, W. Swieszkowski, K. J. Kurzydlowski, and S. Ramakrishna, “Electrospun bio-composite P(LLA-CL)/collagen I/collagen III scaffolds for nerve tissue engineering,” *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, vol. 100B, no. 4, 2012, doi: 10.1002/jbm.b.32676.

[106] Y.-C. Lin, F. Tan, K. G. Marra, S.-S. Jan, and D.-C. Liu, “Synthesis and characterization of collagen/hyaluronan/chitosan composite sponges for potential biomedical applications,” *Acta Biomaterialia*, vol. 5, no. 7, Sep. 2009, doi: 10.1016/j.actbio.2009.03.038.

[107] L. Pastorino, E. Dellacasa, S. Scaglione, M. Giulianelli, F. Sbrana, M. Vassalli, and C. Ruggiero, “Oriented collagen nanocoatings for tissue

engineering," *Colloids Surfaces B: Biointerfaces*, vol. 114, pp. 372–378, Feb. 2014, doi: 10.1016/j.colsurfb.2013.10.026.

[108] M. Prabhakaran, E. Vatankhah, and S. Ramakrishna, "Electrospun aligned PHBV/collagen nanofibers as substrates for nerve TE," *Biotechnology and Bioengineering*, vol. 110, Oct. 2013, doi: 10.1002/bit.24937.

[109] A. Sionkowska and J. Kozłowska, "Characterization of collagen/hydroxyapatite composite sponges as a potential bone substitute," *International Journal of Biological Macromolecules*, vol. 47, no. 4, Nov. 2010, doi: 10.1016/j.ijbiomac.2010.07.002.

[110] K. Wei, Y. Li, X. Lei, H. Yang, A. Teramoto, J. Yao, K. Abe, and F. K. Ko, "Emulsion electrospinning of a collagen-like protein/PLGA fibrous scaffold: Empirical modeling and preliminary release assessment of encapsulated protein," *Macromolecular Bioscience*, vol. 11, no. 11, 2011, doi: 10.1002/mabi.201100141.

[111] M. Maas P. Guo, M. Keeney, F. Yang, T. M. Hsu, G. G. Fuller, C. R. Martin, and R. N. Zare, "Preparation of mineralized nanofibers: Collagen fibrils containing calcium phosphate," *Nano Letters*, vol. 11, pp. 1383–1388, Mar. 2011, doi: 10.1021/nl200116d.

[112] R.-N. Chen, H.-O. Ho, and M.-T. Sheu, "Characterization of collagen matrices crosslinked using microbial transglutaminase," *Biomaterials*, vol. 26, no. 20, Jul. 2005, doi: 10.1016/j.biomaterials.2004.11.012.

[113] J. W. Drexler and H. M. Powell, "Regulation of electrospun scaffold stiffness via coaxial core diameter," *Acta biomaterialia*, vol. 7, no. 3, Mar. 2011, doi: 10.1016/j.actbio.2010.10.025.

[114] M. Shakir, R. Jolly, M. S. Khan, N. e Iram, and H. M. Khan, "Nano-hydroxyapatite/chitosan–starch nanocomposite as a novel bone construct: Synthesis and in vitro studies," *International Journal of Biological Macromolecules*, vol. 80, pp. 282–292, Sep. 2015, doi: 10.1016/j.ijbiomac.2015.05.009.

[115] C. M. Tierney, M. G. Haugh, J. Liedl, F. Mulcahy, B. Hayes, and F. J. O'Brien, "The effects of collagen concentration and crosslink density on the biological, structural and mechanical properties of collagen-GAG scaffolds for bone tissue engineering," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 2, no. 2, Apr. 2009, doi: 10.1016/j.jmbbm.2008.08.007.

[116] T. Kokubo and H. Takadama, "How useful is SBF in predicting in vivo bone bioactivity?," *Biomaterials*, vol. 27, no. 15, May 2006, doi: 10.1016/j.biomaterials.2006.01.017.

[117] L. Kong, Y. Gao, G. Lu, Y. Gong, N. Zhao, and X. Zhang, "A study on the bioactivity of chitosan/nano-hydroxyapatite composite scaffolds for bone tissue engineering," *European Polymer Journal*, vol. 42, no. 12, Dec. 2006, doi: 10.1016/j.eurpolymj.2006.08.009.

[118] M. E. Hoque, T. Nuge, T. K. Yeow, and N. Nordin, "Gelatin based scaffolds for tissue engineering – A review," *Polymer Research Journal*, vol. 9, no. 1, p. 19, 2015.

[119] S. V. Vlierberghe, P. Dubruel, and E. Schacht, "Biopolymer-based hydrogels as scaffolds for tissue engineering applications: A review," *Biomacromolecules*, vol. 12, no. 5, pp. 1387–1408, May 2011, doi: 10.1021/bm200083n.

[120] S. Bozzini, P. Petrini, L. Altomare, and M. Tanzi, "Fabrication of chemically cross-linked porous gelatin matrices," *Journal of Applied Biomaterials Biomechanics (JABB)*, vol. 7, pp. 194–199, Sep. 2009.

[121] P. Dubruel R. Unger, S. V. Vlierberghe, V. Cnudde, P. J. S. Jacobs, E. Schacht, and C. J. Kirkpatrick, "Porous gelatin hydrogels: 2. in vitro cell interaction study," *Biomacromolecules*, vol. 8, pp. 338–44, Mar. 2007, doi: 10.1021/bm0606869.

[122] K. Hu, F. Cui, Q. Lv, J. Ma, Q. Feng, L. Xu, and D. Fan, "Preparation of fibroin/recombinant human-like collagen scaffold to promote fibroblasts compatibility," *Journal of Biomedical Materials Research Part A*, vol. 84, no. 2, pp. 483–490, Feb. 2008, doi: 10.1002/jbm.a.31440.

[123] A. Steinbüchel and R. H. Marchessault, "Biopolymers for medical and pharmaceutical applications," 2005. [Online]. Available: https://agris.fao.org/agris-search/search.do?recordID=US201300106381

[124] P. M. Visakh and S. Thomas, "Preparation of bionanomaterials and their polymer nanocomposites from waste and biomass," *Waste Biomass Valorization*, vol. 1, no. 1, Mar.

2010, doi: 10.1007/s12649-010-9009-7.

[125] J. W. Weisel, "Fibrinogen and Fibrin," *Advances in Protein Chemistry*, vol. 70, pp. 247–299, 2005, doi: 10.1016/S0065-3233(05)70008-5.

[126] M. S. Park, S.-S. Kim, S.-W. Cho, C. Y. Choi, and B.-S. Kim, "Enhancement of the osteogenic efficacy of osteoblast transplantation by the sustained delivery of basic fibroblast growth factor," *Journal of Biomedical Materials Research Part B Applied Biomaterials*, vol. 79B, no. 2, pp. 353–359, 2006, doi: https://doi.org/10.1002/jbm.b.30549.

[127] I. Kong, K. Y. Tshai, and M. E. Hoque, "Manufacturing of natural fibre-reinforced polymer composites by solvent casting method," in *Manufacturing of Natural Fibre Reinforced Polymer Composites*. New York: Springer International Publishing, 2015, pp. 331–349.

[128] E. Saiz, E. A. Zimmermann, J. S. Lee, U. G. K. Wegst, and A. P. Tomsia, "Perspectives on the role of nanotechnology in bone tissue engineering," *Dental Materials*, vol. 29, no. 1, Jan. 2013, doi: 10.1016/j.dental.2012.08.001.

[129] P. R. Chawla, I. B. Bajaj, S. A. Survase, and R. S. Singhal, "Microbial cellulose: Fermentative production and applications," *Food Technology and Biotechnology*, vol. 47, no. 2, Jun. 2009.

[130] B. Fan, K. Zhang, X.-F. Jiang, L. Ying, F. Huang, and Y. Cao, "High-performance nonfullerene polymer solar cells based on imide-functionalized wide-bandgap polymers," *Advanced Materials Deerfield Beach Fla*, vol. 29, no. 21, Jun. 2017, doi: 10.1002/adma.201606396.

[131] L.-H. Fu, C. Qi, Y.-J. Liu, W.-T. Cao, and M.-G. Ma, "Sonochemical synthesis of cellulose/hydroxyapatite nanocomposites and their application in protein adsorption," *Scientific Reports*, vol. 8, no. 1, May 2018, doi: 10.1038/s41598-018-25566-7.

[132] P. Muangman, S. Opasanon, S. Suwanchot, and O. Thangthed, "Efficiency of microbial cellulose dressing in partial-thickness burn wounds," *Journal of the American College of Clinical Wound Specialists*, vol. 3, no. 1, Mar. 2011, doi: 10.1016/j.jcws.2011.04.001.

[133] S. G. Kumbhar and S. H. Pawar, "Self-functionalized, oppositely charged chitosan-alginate scaffolds for biomedical applications," *BioTechnology: An Indian Journal*, vol. 13, no. 2, pp. 1–15, Mar. 2017.

[134] Sharecare, "What are the five types of wounds? | Injuries, Wound and Trauma," 2021. [Online]. Available: https://www.sharecare.com/health/injuries-wound-trauma/what-are-five-types-wounds

[135] Healthline, "Stages of Wound Healing: 4 Stages and What to Expect," 2019. [Online]. Available: https://www.healthline.com/health/skin/stages-of-wound-healing

[136] H. Adeli, M. T. Khorasani, and M. Parvazinia, "Wound dressing based on electrospun PVA/chitosan/starch nanofibrous mats: Fabrication, antibacterial and cytocompatibility evaluation and in vitro healing assay," *International Journal of Biological Macromolecules*, vol. 122, pp. 238–254, Feb. 2019, doi: 10.1016/j.ijbiomac.2018.10.115.

[137] D. Arora, N. Sharma, V. Sharma, V. Abrol, R. Shankar, and S. Jaglan, "An update on polysaccharide-based nanomaterials for antimicrobial applications," *Applied Microbiology and Biotechnology*, vol. 100, no. 6, Mar. 2016, doi: 10.1007/s00253-016-7315-0.

[138] G.-M. Weng, M. Mariano, J. Lipton, and A. D. Taylor, "MXene films, coatings, and bulk processing," in *2D Metal Carbides and Nitrides (MXenes): Structure, Properties and Applications*. New York: Springer International Publishing, 2019, pp. 197–219.

[139] S. M. Ahsan, M. Thomas, K. K. Reddy, S. G. Sooraparaju, A. Asthana, and I. Bhatnagar, "Chitosan as biomaterial in drug delivery and tissue engineering," *International Journal of Biological Macromolecules*, vol. 110, pp. 97–109, Apr. 2018, doi: 10.1016/j.ijbiomac.2017.08.140.

[140] ScienceDirect, "Drug Delivery," 2021. [Online]. Available: https://www.sciencedirect.com/topics/engineering/drug-delivery

[141] National Institute of Biomedical Imaging and Bioengineering, "Drug Delivery Systems," 2021. [Online]. Available: https://www.nibib.nih.gov/science-education/science-topics/drug-delivery-systems-getting-drugs-their-targets-controlled-manner

[142] M. Rahim and M. R. H. M. Haris, "Banana trunk fibers (BF) immobilized in chitosan (CS) natural composites (BF-i-CS), and its application in controlled-release of pesticides," *Journal of Natural Fibers*, Nov. 2019, doi: 10.1080/15440478.2019.1691119.

[143] J. Vikas, J. Shikha, and S. C. Mahajan, "Nanomedicines based drug delivery systems for anti-cancer targeting and treatment," *Current Drug Delivery*, vol. 12, no. 2, pp. 177–191, Mar. 2015.

[144] A. Ataee, Y. Li, D. Fraser, G. Song, and C. Wen, "Anisotropic Ti-6Al-4V gyroid scaffolds manufactured by electron beam melting (EBM) for bone implant applications," *Materials and Design*, vol. 137, pp. 345–354, Jan. 2018, doi: 10.1016/j.matdes.2017.10.040.

[145] A. Cigada, M. Cabrini, and P. Pedeferri, "Increasing of the corrosion resistance of the Ti6Al4V alloy by high thickness anodic oxidation," *Journal of Materials Science: Materials in Medicine*, vol. 3, no. 6, pp. 408–412, Nov. 1992, doi: 10.1007/BF00701236.

[146] S. R. Paital and N. B. Dahotre, "Calcium phosphate coatings for bio-implant applications: Materials, performance factors, and methodologies," *Materials Science & Engineering R: Report*, vol. 66, no. 1, pp. 1–70, Aug. 2009, doi: 10.1016/j.mser.2009.05.001.

[147] Total Materia, "Properties and Applications of Titanium - 6% Aluminum - 4% Vanadium Alloy," 2021. [Online]. Available: https://www.totalmateria.com/Article86.htm

[148] F. Guillemot, "Recent advances in the design of titanium alloys for orthopedic applications," *Expert Review of Medical Devices*, vol. 2, no. 6, pp. 741–748, Nov. 2005, doi: 10.1586/17434440.2.6.741.

[149] P. C. Rath, L. Besra, B. P. Singh, and S. Bhattacharjee, "Titania/hydroxyapatite bi-layer coating on Ti metal by electrophoretic deposition: Characterization and corrosion studies," *Ceramics International*, vol. 38, no. 4, pp. 3209–3216, May 2012, doi: 10.1016/j.ceramint.2011.12.026.

[150] I. Karacan, B. Ben-Nissan, H. A. Wang, A. Juritza, M. V. Swain, W. H. Müller, J. Chou, A. Stamboulis, I. J. Macha, and V.Taraschi, "Mechanical testing of antimicrobial biocomposite coating on metallic medical implants as drug delivery system," *Materials Science and Engineering: C*, vol. 104, p. 109757, Nov. 2019, doi: 10.1016/j.msec.2019.109757.

[151] S. Farah, D. G. Anderson, and R. Langer, "Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review," *Advanced Drug Delivery Reviews*, vol. 107, pp. 367–392, Dec. 2016, doi: 10.1016/j.addr.2016.06.012.

[152] A. Lasprilla, G. Martinez, B. Lunelli, J. E. Jaimes Figueroa, A. Jardini, and R. Filho, "Synthesis and characterization of poly (Lactic Acid) for use in biomedical field," *Chemical Engineering Transactions*, vol. 24, p. 985, Jan. 2011, doi: 10.3303/CET1124165.

[153] L. Nikolic, I. Ristic, B. Adnadjevic, V. Nikolic, J. Jovanovic, and M. Stankovic, "Novel microwave-assisted synthesis of poly(D,L-lactide): The influence of monomer/initiator molar ratio on the product properties," *Sensors*, vol. 10, no. 5, pp. 5063–5073, May 2010, doi: 10.3390/s100505063.

[154] A. Sharif, S. Mondal, and M. E. Hoque, "Polylactic acid (PLA)-based nanocomposites: Processing and properties," in *Bio-based Polymers and Nanocomposite : Preparation, Processing, Properties & Performance*. New York: Springer International Publishing, 2019, pp. 233–254.

[155] A. K. Nayak and M. S. Hasnain, *Alginates in Drug Delivery*. Massachusetts: Academic Press, 2020.

[156] G. I. Olivas and G. V. Barbosa-Cánovas, "Alginate–calcium films: Water vapor permeability and mechanical properties as affected by plasticizer and relative humidity," *LWT - Food Science and Technology*, vol. 41, no. 2, pp. 359–366, Mar. 2008, doi: 10.1016/j.lwt.2007.02.015.

[157] C. Remuñán-López and R. Bodmeier, "Mechanical, water uptake and permeability properties of crosslinked chitosan glutamate and alginate films," *Journal of Controlled Release*, vol. 44, no. 2, pp. 215–225, Feb. 1997, doi: 10.1016/S0168-3659(96)01525-8.

[158] K. Y. Lee and D. J. Mooney, "Alginate: Properties and biomedical applications," *Progress in Polymer Science*, vol. 37, no. 1, pp. 106–126,

Jan. 2012, doi: 10.1016/j.progpolymsci.2011.06.003.

[159] R. Deepika, K. Girigoswami, R. Murugesan, and A. Girigoswami, "Influence of divalent cation on morphology and drug delivery efficiency of mixed polymer nanoparticles," *Current Drug Delivery*, vol. 15, no. 5, pp. 652–657, Jun. 2018, doi: 10.2174/1567201814666170825160617.

[160] N. Formisano, N. Bhalla, M. Heeran, J. R. Martinez, A. Sarkar, M. Laabei, P. Jolly, C. R. Bowen, J. T. Taylor, S. Flitsch, and P. Estrela, "Inexpensive and fast pathogenic bacteria screening using field-effect transistors," *Biosensors and Bioelectronics*, vol. 85, pp. 103–109, Nov. 2016, doi: 10.1016/j.bios.2016.04.063.

[161] ScienceDirect, "Biosensing," 2021. [Online]. Available: https://www.sciencedirect.com/topics/engineering/biosensing

[162] E. Zacco, M. I. Pividori, and S. Alegret, "Electrochemical biosensing based on universal affinity biocomposite platforms," *Biosensors and Bioelectronics*, vol. 21, no. 7, pp. 1291–1301, Jan. 2006, doi: 10.1016/j.bios.2005.05.016.

[163] W. Chen Q. Li, Y. Wang, X. Yi, J. Zeng, H. Yu, Y. Liu, and J. Li, "Comparative study of aerogels obtained from differently prepared nanocellulose fibers," *ChemSusChem*, vol. 7, no. 1, pp. 154–161, Jan. 2014, doi: 10.1002/cssc.201300950.

[164] S. S. Kistler, "Coherent Expanded-Aerogels," *The Journal of Physical Chemistry*, vol. 36, no. 1, pp. 52–64, Jan. 1932, doi: 10.1021/j150331a003.

[165] H. P. S. A. Khalil, A. S. Adnan, E. B. Yahya, N. G. Olaiya, S. Safrida, Md. S. Hossain, V. Balakrishnan, D. A. Gopakumar, C. K. Abdullah, A. A. Oyekanmi, and D. Pasquini, "A review on plant cellulose nanofibre-based aerogels for biomedical applications," *Polymers*, vol. 12, no. 8, Aug. 2020, doi: 10.3390/polym12081759.

[166] X. Wang, M. Han, J. Bao, W. Tu, and Z. Dai, "A superoxide anion biosensor based on direct electron transfer of superoxide dismutase on sodium alginate sol–gel film and its application to monitoring of living cells," *Analytica Chimica* Acta, vol. 717, pp. 61–66, Mar. 2012, doi: 10.1016/j.aca.2011.12.045.

[167] V. Buk, E. Emregul, and K. C. Emregul, "Alginate copper oxide nano-biocomposite as a novel material for amperometric glucose biosensing," *Materials Science and Engineering: C*, vol. 74, pp. 307–314, May 2017, doi: 10.1016/j.msec.2016.12.003.

[168] J. Davies, "Where have all the antibiotics gone?," *Candian Journal of Infectious Diseases Medical Microbiology*, vol. 17, no. 5, 2006, doi: 10.1155/2006/707296.

[169] A. Dvorzhinskiy, G. Perino, R. Chojnowski, M. Van Der Meulen, F. Ross, M. Bostrom, and X. Yang, "Cerament bone void filler with gentamicin increases bone formation and decreases detectable infection in a rat model of debrided osteomyelitis," *Orthopaedic Proceedings*, vol. 97-B, no. SUPP_16, Dec. 2015, doi: 10.1302/1358-992X.97BSUPP_16.EBJIS2015-009.

[170] M. Nilsson, J.-S. Wang, L. Wielanek, K. E. Tanner, and L. Lidgren, "Biodegradation and biocompatability of a calcium sulphate-hydroxyapatite bone substitute," *Journal of Bone Joint Surgery British*, vol. 86-B, no. 1, Jan. 2004, doi: 10.1302/0301-620X.86B1.14040.

[171] D. Raina, A. Gupta, M. Petersen, W. Hettwer, M. Nally, M. Tägil, M. Zheng, A. Kumar, and L. Lidgren, "A biphasic bone substitute with gentamycin regenerates bone in osteomyelitis with muscle acting as an osteoinductive niche," *Orthopaedic Proceedings*, vol. 97-B, no. SUPP_16, Dec. 2015, doi: 10.1302/1358-992X.97BSUPP_16.EBJIS2015-024.

[172] S. Chen, J. W. Chen, B. Guo, and C. C. Xu, "Preoperative antisepsis with chlorhexidine versus povidone-iodine for the prevention of surgical site infection: A systematic review and meta-analysis," *World Journal of Surgery*, vol. 44, no. 5, May 2020, doi: 10.1007/s00268-020-05384-7.

[173] Wikipedia, "Rifampicin," 2021. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Rifampicin&oldid=1020073085

[174] M. A. McNally, J. Y. Ferguson, A. C. K. Lau, M. Diefenbeck, M. Scarborough, A. J. Ramsden, and B. L. Atkins, "Single-stage treatment of chronic osteomyelitis with a new absorbable, gentamicin-loaded, calcium sulphate/hydroxyapatite biocomposite," *Bone and Joint*

Journal, vol. 98-B, no. 9, pp. 1289–1296, Sep. 2016, doi: 10.1302/0301-620X.98B9.38057.

[175] T. Lu, Q. Li, W. Chen, and H. Yu, "Composite aerogels based on dialdehyde nanocellulose and collagen for potential applications as wound dressing and tissue engineering scaffold," *Composites Science and Technology*, vol. 94, pp. 132–138, Apr. 2014, doi: 10.1016/j.compscitech.2014.01.020.

[176] M. Power, B. Hosticka, E. Black, C. Daitch, and P. Norris, "Aerogels as biosensors: Viral particle detection by bacteria immobilized on large pore aerogel," *Journal of Non-Crystalline Solids*, vol. 285, no. 1, pp. 303–308, Jun. 2001, doi: 10.1016/S0022-3093(01)00471-9.

[177] J. V. Edwards, K. R. Fontenot, N. T. Prevost, N. Pircher, F. Liebner, and B. D. Condon, "Preparation, characterization and activity of a peptide-cellulosic aerogel protease sensor from cotton," *Sensors*, vol. 16, no. 11, Nov. 2016, doi: 10.3390/s16111789.

[178] J. Bhandari, H. Mishra, P. K. Mishra, R. Wimmer, F. J. Ahmad, and S. Talegaonkar, "Cellulose nanofiber aerogel as a promising biomaterial for customized oral drug delivery," *International Journal of Nanomedicine*, vol. 12, pp. 2021–2031, Mar. 2017, doi: 10.2147/IJN.S124318.

[179] B. Fang, Y.-Z. Wan, T.-T. Tang, C. Gao, and K.-R. Dai, "Proliferation and osteoblastic differentiation of human bone marrow stromal cells on hydroxyapatite/bacterial cellulose nanocomposite scaffolds," *Tissue Engineering Part A*, vol. 15, no. 5, Jan. 2009, doi: 10.1089/ten.tea.2008.0110.

[180] F. Yoshii, L. Zhao, R. A. Wach, N. Nagasawa, H. Mitomo, and T. Kume, "Hydrogels of polysaccharide derivatives crosslinked with irradiation at paste-like condition," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interaction Material and Atoms*, vol. 208, pp. 320–324, Aug. 2003, doi: 10.1016/S0168-583X(03)00624-4.

[181] F. Liebner, E. Haimer, M. Wendland, M.-A. Neouze, K. Schlufter, P. Miethe, T. Heinze, A. Potthast, and T. Rosenau, "Aerogels from unaltered bacterial cellulose: Application of $scCO_2$ drying for the preparation of shaped, ultra-lightweight cellulosic aerogels," *Macromolecular Bioscience*, vol. 10, no. 4, pp. 349–352, 2010, doi: https://doi.org/10.1002/mabi.200900371.

[182] J. Zhou and Y.-L. Hsieh, "Conductive polymer protonated nanocellulose aerogels for tunable and linearly responsive strain sensors," *ACS Applied Materials & Interfaces*, vol. 10, no. 33, pp. 27902–27910, Aug. 2018, doi: 10.1021/acsami.8b10239.

[183] S. J. Christian, "8 - Natural fibre-reinforced noncementitious composites (biocomposites)," in *Nonconventional and Vernacular Construction Materials*. 2nd ed., Cambridge, UK: Woodhead Publishing, 2020, pp. 169–187.

[184] O. Faruk and M. S. Ain, "Biofiber reinforced polymer composites for structural applications," in *Developments in Fiber-Reinforced Polymer (FRP) Composites for Civil Engineering*. Cambridge, UK: Woodhead Publishing, 2013, pp. 18–53. doi: 10.1533/9780857098955.1.18.

[185] D. B. Dittenber and H. V. S. GangaRao, "Critical review of recent publications on use of natural composites in infrastructure," *Composites Part A: Applied Science and Manufacturing*, vol. 43, no. 8, Aug. 2012, doi: 10.1016/j.compositesa.2011.11.019.

[186] S. B. Hosseini, "Chapter 13 - Natural fiber polymer nanocomposites," in *Fiber-Reinforced Nanocomposites: Fundamentals and Applications*. Amsterdam, Netherlands: Elsevier, 2020, pp. 279–299. doi: 10.1016/B978-0-12-819904-6.00013-X.

[187] P. Bhagabati, "Chapter 9 - Biopolymers and biocomposites-mediated sustainable high-performance materials for automobile applications," in *Sustainable Nanocellulose and Nanohydrogels from Natural Sources*. Amsterdam, Netherlands: Elsevier, 2020, pp. 197–216.

[188] A. S. Getme and B. Patel, "A review: Bio-fiber's as reinforcement in composites of polylactic acid (PLA)," *Materials Today: Proceedings*, vol. 26, pp. 2116–2122, Jan. 2020, doi: 10.1016/j.matpr.2020.02.457.

[189] R. Siakeng, M. Jawaid, H. Ariffin, S. M. Sapuan, M. Asim, and N. Saba, "Natural fiber reinforced polylactic acid composites: A review," *Polymer Composites*, vol. 40, no. 2, 2019, doi: https://doi.org/10.1002/pc.24747.