Potential Use of Plant Fibres and their Composites for Biomedical Applications

Farideh Namvar,[a,b,*] Mohammad Jawaid,[a,g] Paridah Md Tahir,[a] Rosfarizan Mohamad,[a,c] Susan Azizi,[d] Alireza Khodavandi,[e] Heshu Sulaiman Rahman,[f] and Majid Dehghan Nayeri [a]

Plant-based fibers such as flax, jute, sisal, hemp, and kenaf have been frequently used in the manufacturing of biocomposites. Natural fibres possess a high strength to weight ratio, non-corrosive nature, high fracture toughness, renewability, and sustainability, which give them unique advantages over other materials. The development of biocomposites by reinforcing natural fibres has attracted attention of scientists and researchers due to environmental benefits and improved mechanical performance. Manufacturing of biocomposites from renewable sources is a challenging task, involving metals, polymers, and ceramics. Biocomposites are already utilized in biomedical applications such as drug/gene delivery, tissue engineering, orthopedics, and cosmetic orthodontics. The first essential requirement of materials to be used as biomaterial is its acceptability by the human body. A biomaterial should obtain some important common properties in order to be applied in the human body either for use alone or in combination. Biocomposites have potential to replace or serve as a framework allowing the regeneration of traumatized or degenerated tissues or organs, thus improving the patients' quality of life. This review paper addresses the utilization of plant fibres and its composites in biomedical applications and considers potential future research directed at environment-friendly biodegradable composites for biomedical applications.

Keywords: Fibres; Polymers; Biocomposites; Biomedical applications

Contact information: a: Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia; b: Mashhad Branch, Islamic Azad University, Mashhad, Iran; c: Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, Serdang, Malaysia; d: Faculty of Chemistry, Universiti Putra Malaysia, Serdang, Malaysia; e: Department of Paramedical Sciences, Gachsaran Branch, Islamic Azad University, Gachsaran, Iran; f: Department of Microbiology and Pathology, Faculty of Veterinary Medicine, Universiti Putra Malaysia, Serdang, Malaysia; g:Department of Chemical Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia; Corresponding author: farideh.namvar@gmail.com*

INTRODUCTION

Natural fibres are of interest to scientists due to advantageous traits such as low cost, high strength to weight ratio, low density per unit volume, non-corrosive property, and acceptable specific strength, in addition to their renewable and degradable characteristics (Joshi *et al.* 2004; Ticoalu 2010; Kalia *et al.* 2009). Compared to synthetic fibres, natural fibres are often available at low cost and cause less health and environmental hazard problems for people producing the composites as compared to glass fibre based composites (Jawaid and Abdul Khalil 2011). Natural fibres can be used for development of highly thermally stable and acoustic insulator materials (Puglia *et al.*

2005a; Biagiotti *et al.* 2004). It is possible to produce highly durable consumer products from natural fibres that can be easily recyclable (Corbie 2001). However, natural fibres generally exhibit poor water resistance, low durability, and poor fibre/matrix interfacial bonding that leads to a loss in final properties of the composites and ultimately hinders their industrial usage (Milanese *et al.* 2011; Puglia *et al.* 2005b; Romanzini *et al.* 2012). Fibre/matrix interfacial bonding in polymer composites can be improved by using coupling agents and/or surface modification techniques (Kalia *et al.* 2009). Abundant amounts of natural fibres are available in nature, and these can be applied as reinforcement or bio-fillers in the manufacturing of polymer composites (Yang *et al.* 2006). In the past few years, demand for natural fibres has shown a dramatic increase for making new types of environmentally–friendly composites (Cheung *et al.* 2009). Natural fibres have been used by people throughout historical times, but in recent years natural fibres application in polymer composites has increased due to their availability as renewable materials and increased concerns about the environment (Majeed *et al.* 2013). Polymer composites are those materials that can be developed by combination of either natural fibers/synthetic resin or natural fibers/bio-resin (Chandramohan and Marimuthu 2011). The properties of polymer composites can be altered by the constituent components and filler which significantly different from those of the individual constituents (Ramakrishna *et al.* 2001).

Biocomposites can be fabricated by combining biofibres such as oil palm, kenaf, industrial hemp, flax, jute, henequen, pineapple leaf fibre, sisal, wood, and various grasses with polymer matrices from either non-renewable (petroleum based) or renewable resources (Jawaid and Khalil 2011). Biocomposites can be employed in bioengineering or biomedical applications (Cheung *et al.* 2009) or alternatively as composites that contain at least one natural fibre/plant fibre component. Presently fibre-reinforced polymer composites are extensively used multiphase materials in orthopedics, and most of the today's upper and lower limb prostheses are made from composites with an underlying polymer matrix (Chandramohan and Marimuthu 2011). The primary reason for the development of biocomposites from natural fibre is flexibility of type/distribution of the reinforcing phases in the composites and the possibility to obtain biocomposites having a wide range of mechanical and biological properties (Ramakrishna *et al.* 2001). Biobased materials such as natural fibers, biopolymers, and biocomposites integrate the principles of sustainability, industrial ecology, eco-efficiency, and green chemistry. They may be engineered into the development of the next generation of materials, products, and processes (Barthelat 2007; Zainudin and Sapuan 2009). Biodegradable and bio-based products based on annually renewable agricultural and biomass feedstock can form the basis for a portfolio of sustainable, eco-efficient products that can compete and capture markets currently dominated by products based exclusively on petroleum feedstock (Mohanty *et al.* 2002). Most of the living tissues such as bone, cartilage, and skin are essentially composites (Meyers *et al.* 2008).

Natural Fibres

Natural fibres are those that are not synthetic or manmade (Garmendia *et al.* 2007). Natural fibres can be obtained from plant fibres such as sisal, hemp, bamboo, coir, flax, kenaf, jute, ramie, oil palm, pineapple, banana, cotton, *etc*., as well as from animal sources, *e.g.* wool, silk, and chicken feather fibres (Mukhopadhyay and Fangueiro 2009). Natural fibres can be divided into six main categories (Fig. 1) depending on the part of the plant from which they are extracted, bast or stem fibers (jute, flax, hemp, ramie, roselle, kenaf, *etc.*), leaf fibers (banana, sisal, manila hemp, agave, abaca, pineapple, *etc*.), seed fibers (coir, cotton, and kapok), fruit fibres (oil palm, coir), stalk (wheat, rice, rye, *etc*.), and grass/reed (bamboo, bagasse, corn, *etc.*) (Jawaid and Abdul Khalil 2011). Traditionally, natural fibers have been cultivated and used comprehensively for non-structural applications and have also been used for applications in housing as roof material and wall insulation. A large variation is found in the properties of natural fibers (Joshi *et al.* 2004). The type of fibers, moisture content, and form of fibers (yarn, woven, twine, chopped, felt, *etc*.) can affect the properties (Navarro *et al.* 2008). Moreover, the properties are also affected by the place where the fibers are grown, cultivation conditions, the part of the plant they are harvested from, the growing period, and any retting or extracting processes (Ticoalu 2010).

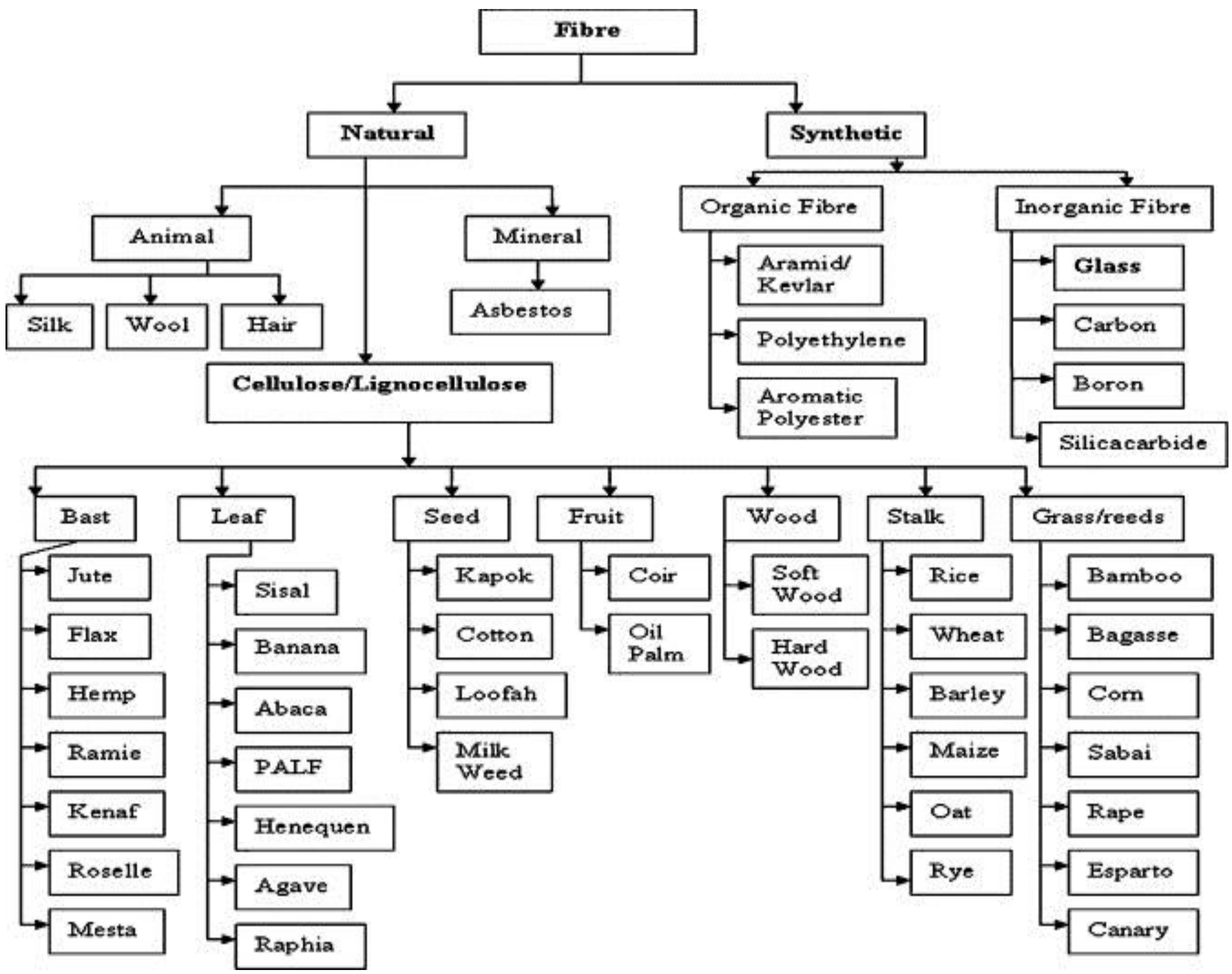

Fig. 1. Classification of natural and synthetic fibres (Jawaid and Khalil 2011 - With Permission)

Table 1 shows mechanical properties of different types of natural fibers for composite applications as compared with human tissue. Human tissue can be grouped into hard (bone and tooth) and soft tissues (skin, blood vessels, cartilage, and ligaments). Hard tissues are stiffer (with higher elastic modulus) and stronger (with higher tensile strength) than the soft tissues. Furthermore, they are essentially composite materials with anisotropic properties that depend on the roles and structural arrangements of various components (*e.g*. collagen, elastin, and hydroxyapatite) of the tissues (Ramakrishna *et al.*

2001). In general, natural fibres have comparable mechanical properties as well as biocompatibility to human tissues, such that often there is no adverse effect on host tissue, which is required for any materials to be used in biomedical applications (Cheung *et al.* 2009). Recent advances in natural fibres based polymer composites have enhanced their application in biomedical applications and offer significant opportunities for improved materials from renewable resources with enhanced support for global sustainability.

Table 1. Mechanical Properties of Natural Fibres for Composite Applications

	Tensile strength (MPa)	**Elongation at break (%)**	**Young modulus (GPa)**
Natural fibres			
Flax	300–1500	1.3–10	24–80
Jute	200–800	1.16–8	10–55
Sisal	80–840	2–25	9–38
Kenaf	295–1191	3.5	2.86
Pineapple	170–1627	2.4	60-82
Banana	529–914	3	27–32
Coir	106–175	14.21–49	4–6
Oil palm (empty fruit)	130–248	9.7–14	3.58
Oil palm (fruit)	80	17	
Ramie	348–938	1.2–8	44–128
Hemp	310–900	1.6–6	30–70
Wool	120–174	25–35	2.3–3.4
Spider silk	875–972	17–18	11–13
Cotton	264–800	3–8	5–12.6
Human tissues			
Hard tissue (tooth, bone, human compact bone, longitudinal direction)	130–160	1–3	17–20
Skin	7.6	78	
Tendon	53–150	9.4–12	1.5
Elastic cartilage	3	30	
Heart valves	0.45–2.6	10–15.3	
Aorta	0.07–1.1	77–81	

Source: Cheung *et al*. 2009

Bio-binders

Bio-binders, commonly known as biopolymers, are compounds obtained from natural resources and consist of monomeric units that are covalently bonded to form larger structures (Asokan *et al.* 2012a). Bio-binders vary with respect to their melt flow indices, impact properties, hardness, vapor transmission characteristics, coefficient of friction, and decomposition (Flory and Requesens 2013). Bio-binders find many applications in a number of fields such as drug delivery system, wound healing, food containers and agricultural films, waste bags, soil retention sheeting, filtration, hygiene and protective clothing, and automobile industries (Wu and Wu 2006). There are many types of bio binders, of which the most common are shown in Fig. 2. From a search of the literature it is clear that fully resorbable biocomposite fracture fixation has been achieved based on the group of PLA (polylactic acid) polymers; PLAs possess two major characteristics that make them an extremely attractive bioabsorbable material: (1) they can degrade inside the body at a rate that can be controlled, *e.g.* by varying molecular weight, the share of their enantiomers L and D-lactide, or copolymerising it with PGA (polyglycolic acid) polymer, and (2) and, if crystallization of the PLA-polymer is prevented, their degradation products are nontoxic, biocompatible, and easily metabolized (Hutmacher *et al.* 2000).

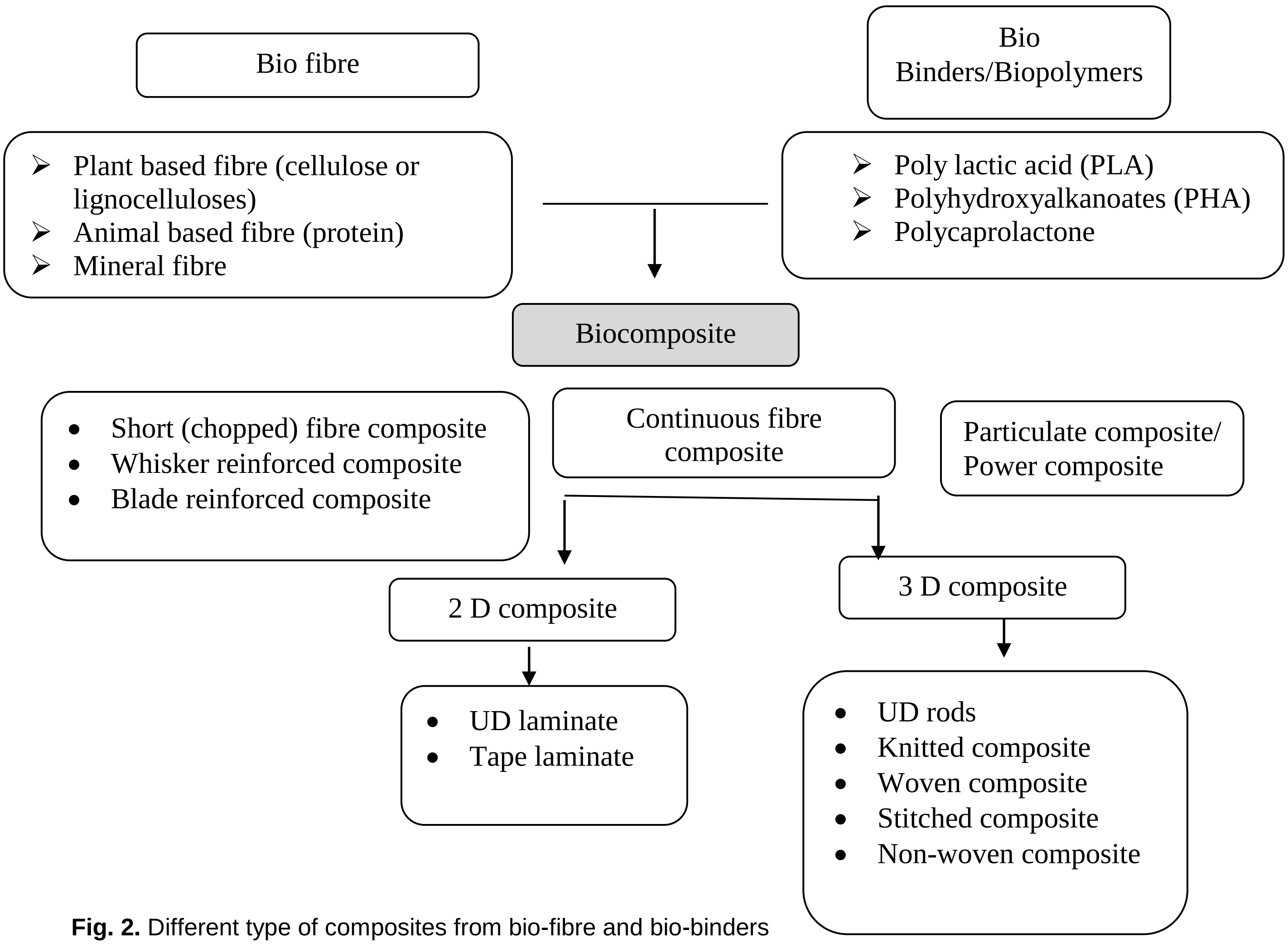

Fig. 2. Different type of composites from bio-fibre and bio-binders

Biocomposites

Polymer composites have been fabricated mainly by using high strength synthetic fibres such as carbon, glass, and aramid and low strength polymeric matrix; such composites have dominated the aerospace, leisure, automotive, construction, sporting industries, and biomedical applications (Cheung *et al.* 2009). Due to the need for more environmental friendly materials, natural fiber composites have been regaining increased attention. Although synthetic fiber such as glass fibers, carbon fibers, and aramid-based composite materials are high performance materials, they are less biodegradable and sourced from non-renewable resources. Researchers and entrepreneurs are interested in the utilization of environmentally friendly and sustainable biocomposite materials for biomedical and industrial applications. Table 2 displays advantages and disadvantages of natural fibres products. Therefore, the use of natural fibers may bring environmental benefits as well as cost benefits.

Table 2. Advantages and Disadvantages of Natural Fibres Products

Advantages of Natural Fibers	Disadvantages of Natural Fibers
1. Environmental Aspects: • renewable resources • low energy requirements during production • carbon dioxide neutrality • disposal by composting	• Lower strength, especially impact strength
2. Biological Aspects: • natural organic products • no dermal issue for their handling • do not pose a bio-hazard upon disposal	• Variable quality, influenced by weather
3. Production Aspects: • non-abrasive • great formability	• Poor moisture resistance which causes swelling of the fibres
4. Component Weight Issues: • lightweight (less than half the density of glass fibers)	• Restricted maximum processing temperature
5. Financial Aspects:	• Lower durability; Poor fire resistance
6. General Aspects: • safer crash behavior in tests (*i.e.*, no splintering) • good thermal insulation and acoustic properties due to their hollow tubular structures • high specific strength • good sound insulation • price fluctuation by harvest results or agricultural politic	• Poor fibre/matrix adhesion

In polymer composites, natural fibres usually provide strength, while the matrix provides binding to the fibres (Verma *et al.* 2013). Natural fibres by themselves cannot be used to sustain the range of loads expected in many biomedical applications (Everitt *et al.* 2013). Therefore, a matrix material is used to bind and protect the natural fibres. Depending on the type of natural fibres, type of matrix, the proportion of fiber-matrix, and the type of manufacturing process, the properties of fiber composites can be tailored to achieve the desired end product (Ticoalu 2010). Both synthetic and bio-resin can be either in the form of thermoset or thermoplastic type of resin. The matrix (the bioresin/synthetic resin) supports the fibrous material (natural fibres) and transfers the stress to the fiber to carry the load in natural fibre-reinforced polymer composites. Biocomposites fabrication can be done by different methods, sometimes placing natural fibre in the desired direction to obtain polymer composites having specific mechanical properties. Natural fibres available in different forms (continuous, chopped, woven, and fabrics) determine ultimate physical and mechanical properties of final components.

Several factors that must be considered to achieve desirable mechanical properties in fibre-reinforced composites include the kind of natural fibres, compatible surface chemistry of the fibre and matrix phases, corresponding surface energies, and the quality of the interface (Cullen *et al.* 2013). The properties of natural fibres vary not only between species but also depend strongly on the cultivation, isolation, and processing methods (Zhu *et al.* 2013). In the case of pulp fibre-reinforced composites, incompatibilities often exist due to the hydrophilic nature of fibre surface and the generally hydrophobic nature of the polymer matrix types that are most widely used (Cullen *et al.* 2013). This leads to insufficient bonding adhesion at the interface, as well as poor fibre dispersion, in turn resulting in non-uniform material properties in the composites (Kabir and Wang 2011). The improvement of mechanical properties of these composites has been an important topic for many researchers (Sarasini *et al.* 2013). Many studies have been carried out to determine the impact of fibre type and processing methods on the tensile strength, modulus, and elongation at break of natural fibre composites (Mueller and Krobjilowski 2004; Mukhopadhyay and Fangueiro 2009; Bledzki and Jaszkiewicz 2010). The following table summarizes some of these results.

Table 3. Mechanical Properties of Different Natural Fibre Composites

Fibre Type	Matrix	Tensile Strength	Increase Tensile Modulus	Tensile Elongation	References
Flax (30%)	PLA	Improved by 65%,	186%	Reduced by 38%	(Bodros *et al.* 2007)
Flax (40%)	PLA	No improvement	110%	Reduced by 55%	Oksman *et al.*2003
Rice Husks, (30%)	PLA	Reduced by 42%	40%	-	(Garcia and Garmendia 2007)
Kenaf (30%)	PlA	Reduced by 10%	72%	-	(Garcia and Garmendia 2007)

Natural fiber composites can be used for biomedical applications for bone and tissues repair and reconstruction (Dhandayuthapani *et al.* 2011). The property (tensile strength) of natural fiber composites has been found to vary depending on the type of fibers (Table 3), and the type of resin and manufacturing process. Figure 3 illustrates fabrication of different types of bio-composites according to their reinforcement forms. It is clear from Fig. 3 that different kinds of reinforcements, *i.e.* short fibers, continuous fibers, and particulates (powders) can be used for fabrication of biocomposites. The main problem of those composites is the coordination of the degradation behavior of both phases and, especially, of the interphase between fibre and matrix.

Biomaterial

The National Institutes of Health Consensus Development Conference defined a biomaterial as “any material or mixture of materials manufactured or natural in base which can be used for any interval of time, as a complete item or as a part of a system which treats, enhances or replaces any tissue, organ, or function of the body” (Patel and Gohil 2012). Biomaterials can also be defined as “materials used in implants or medical devices and intent or compatible to interact with biological systems” (Ratner and Hoffman 2004). Human beings have been utilizing biomaterials from ancient times:

Egyptian mummies, as well as artificial teeth, eyes, noses, and ears have been found. Indian and Chinese craftspeople have been utilizing glues, waxes, and tissues to repair or regenerate abnormal parts of the body as a traditional treatment of wounded or traumatized patients (Patel and Gohil 2012). Over the centuries, improvements in synthetic materials, surgical techniques, and sterilization methods have permitted the use of biomaterials in many ways. Ideally, these biomaterials must be nontoxic, non-carcinogenic, chemically inert, stable, and mechanically strong enough to withstand the repeated forces of a lifetime.

Selection of Biomaterials for Biomedical Applications

A biomaterial used for implant should possess some important properties in order to allow long-term usage in the body without rejection. There are several factors and issues required to be considered before choosing appropriate natural fibres composites for biomedical and engineering applications such as biodegradability, bioresorbability, biocompatibility, sterilizability, functionability, manufacturability, as well as mechanical and thermal properties (Ambrose and Clanton 2004; DiGregorio 2009; Hin 2004). In another study, researchers reported that several additional issues such as biological response, biocompatibility, and flexibility must be considered for designing biomedical composites and predicting their performance (Kutz *et al.* 2003). Biocompatibility is an important factor that can distinguish between the chemical, biological, and physical suitability of materials and its compatibility in terms of mechanical properties (stiffness, strength, optimum loading) at the implant/tissue interface (Ramakrishna *et al.* 2001). The design and selection of biomaterials depend on different properties that are summarized in Table 4. Moreover, it should be noted that success of biomaterials in the body depends on surgical techniques, health conditions, and way of life of patients (Ramakrishna *et al*. 2001). For example, the longitudinal mechanical properties of cortical bone are higher than the transverse direction properties. The anisotropy of the elastic properties of the biological tissues has to be considered as an essential design criterion for implants made from composite biomaterials.

Many materials can be used in biomedical applications and they may be grouped into (a) metals, (b) ceramics, (c) polymers, and (d) composites. These four classes are used singly and in combination to form most of the implantation devices available on the market (Table 5). Metals or ceramics seem to be more suitable for hard tissue applications from the mechanical point of view as compared to polymers for soft tissue applications. On the other hand, the elastic moduli of metals and ceramics are 10 to 20 times higher than those of the hard tissues. Thus, implants made from these materials tend to be much stiffer than the tissue to which they are attached. In orthopedic surgery, this mismatch of stiffness between the bone and the metallic or ceramic implants influences the load at the implant/tissue interface. Since the extent of stress carried by bone and metallic or ceramic implant is directly related to their stiffness; bone is insufficiently loaded compared to the implant. Wolffs law of stress related bone remodeling states that it will lead to lower bone density and altered bone architecture (Goldstein *et al.* 1991). In osteosynthesis, this may affect healing of the fractured bones and may increase the risk of refracture of the bone after removal of the osteosynthesis implant, *e.g.* bone plate.

Table 4. Key Factors for the Selection of Materials for Biomedical Applications

Factors	Description		
	Chemical/biological characteristics	**Physical characteristics**	**Mechanical/structural characteristics**
1st Level material properties	•Chemical composition (bulk and surface)	•Density	•Elastic modulus •Shear modulus •Poisson's ratio •Yield strength •Compressive strength
2nd Level material properties	•Adhesion	•Surface topology •Texture •Roughness	•Hardness •Flexural modulus •Flexural strength
Specific functional requirements (based on applications)	•Biofunctionality •Bioinert •Bioactive •Biostability •Biodegradation behavior	•Form and geometry •Coefficient of thermal expansion •Electrical conductivity •Color, aesthetics •Refractive index •Opacity or translucency	•Stiffness or rigidity •Fracture toughness •Fatigue strength •Creep resistance •Friction and wear resistance •Adhesion strength •Impact strength •Proof stress •Abrasion resistance
Processing & Fabrication	•Reproducibility, quality, sterilizability, packaging, secondary processability		
Characteristics of host: tissue, organ, species, age, sex, race, health condition, activity, systemic response			
Medical/surgical procedure, period of application/usage			
Cost			

Source: Ramakrishna *et al.* 2001

In this respect, the use of low-modulus materials such as polymers appears interesting because low strength associated with a lower modulus usually impairs their potential use. Since fiber-reinforced polymers, *i.e.* polymer composite materials, offer both low elastic modulus and high strength, they have been proposed for several orthopedic applications (Table 1). Another merit of a fibre-reinforced polymer is that it is possible to obtain properties and design of an implant to suit the mechanical and physiological conditions of the host tissues by variation of volume fractions and arrangement of reinforcement phase. Therefore, composite materials offer a greater potential of structural biocompatibility than the homogenous monolithic materials. Biomedical devices fabricated from composite materials are anti-corrosive and have high fracture toughness and higher resistance against fatigue failure as compared to metal alloys and ceramics (Teoh 2000).

Table 5. Mechanical Properties of Different Biomedical Materials Classes

Mechanical properties / biomedical materials classes	Elastic modulus (GPa)	Tensile Strength (MPa)
Metal		
Ti-alloys	116	965
Amalgam	30	58
Ti-6Al-4V	15–30	70–150
stainless steel	210	600
316L	120	900
Co-Cr Alloys	210	1085
Ceramics		
Alumina	380	300
Zirconia	220	820
Bioglass	35	42
Hydroxyapatite(HA)	95	50
Polymers		
Polyurethane(PE)	0.8-22	30-40
Polyurethane (PU)	0.02-0.9	21-40
Polytetrafuoroethylene (PTFE)	0.5-2	
Polyacetal (PA)	2.1	67
Polymethylmethacrylate (PMMA)	0.6–2.55	23–59
Polyethylene Terepthalate (PET)	2.85	61
Silicone Rubber (SR)	0.008	7.6
Polyetheretherketone (PEEK)	8.3	139
Poly(lactic acid) (PLA)		
Polysulfone (PS)	2.65	75

Source: Black and Hasting 1998; Cheung *et al.* 2009; Ramakrishna *et al.* 2001.

Applications

Commercial usage of biomaterials obtained from sustainable materials has been significantly rising due to increasing prices of petroleum products and the demand for environmental friendly and sustainable biomedical devices. Innovations in the composite material design and fabrication processes are raising the possibility of realizing implants with improved performance by using plant fibres based biocomposites. However, for successful application, surgeons must be convinced of the long term durability and reliability of composite biomaterials. Recently, ongoing work has explored the use of palm tree fibres for industrial and biomedical applications (Anon 2013). In the cited study, researchers planned to utilize the hybrid fibres of Egyptian and Qatari palm tree with starch, water, and glycerin to fabricate materials that cost little to manufacture but possess high strength for industrial and biomedical applications. A schematic diagram shows the potential use of biocomposites in the repair, reconstruction, and replacement of human hard tissues (Fig. 3).

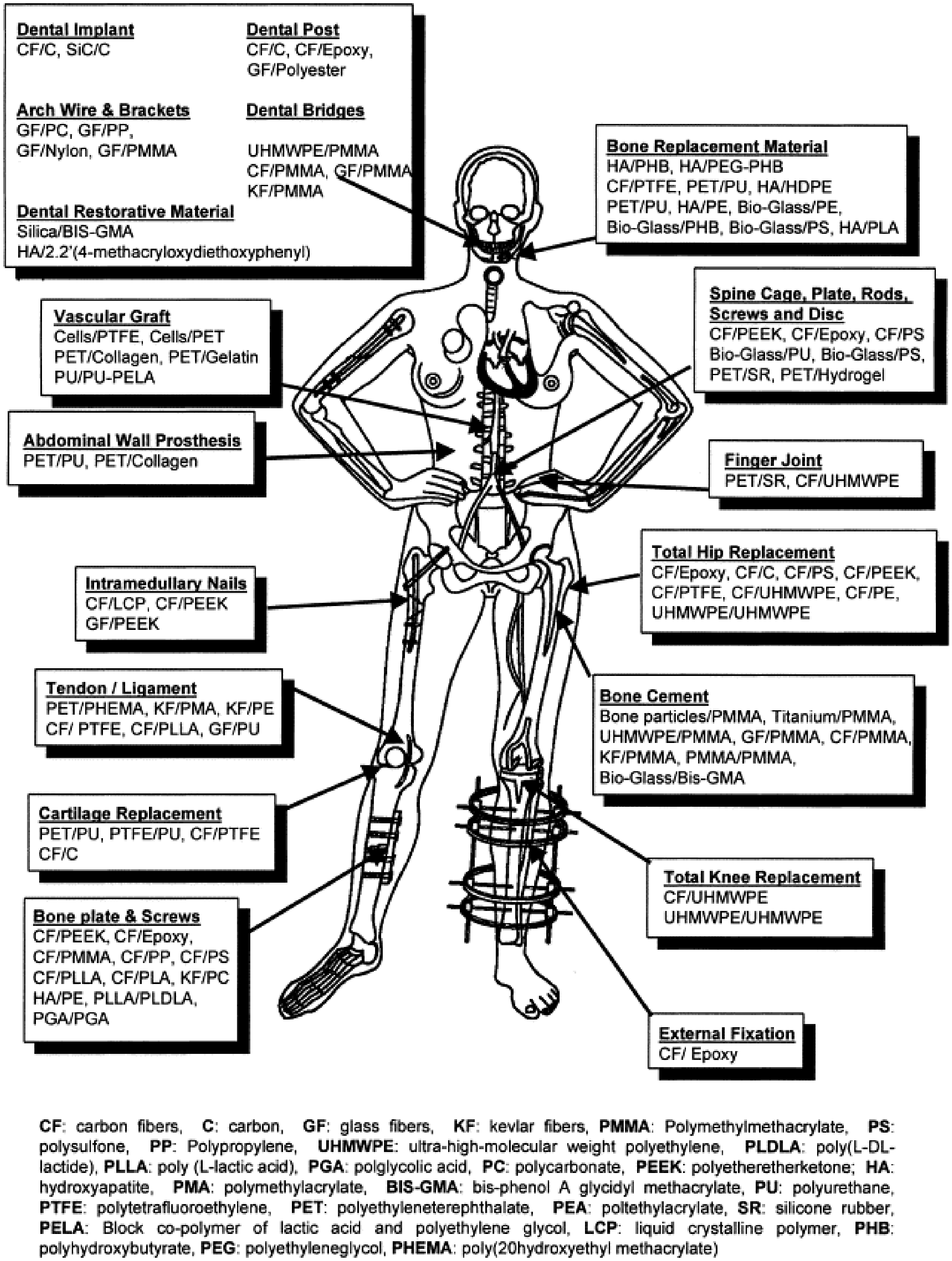

Fig. 3. Various applications of different polymer composite biomaterials
(Source: Ramakrishna *et al*. 2001; With Permission)

Casting materials (composite materials made of woven cotton fabrics) have been used to form splints, casts, and braces to fix bone fragments (Ramakrishna *et al.* 2001). Other researchers also reported that traditional plant-originated cellulose and cellulose-based materials (woven cotton gauze dressings) have been used in medical applications for many years and are mainly utilized to stop bleeding (Czaja *et al.* 2007; Daunton and Kothari 2012). It is also known that plant cellulose can be used as a clinical application in wound-healing research as a factor which stimulates granulation tissue in the wound bed after damage (Morgan and Nigam 2013).

Cellulosic nanofibres obtained from plant fibres have unique mechanical, electrical, chemical, and optical properties that can be utilized for diverse applications. Pineapple leaf fibres (PALF) have been reported to be very versatile material with promise for a wide range of biomedical and biotechnology applications such as tissue engineering, drug delivery, wound dressing, and medical implants (Cherian *et al.* 2010). The same authors also reported development of nanocomposites from PALF nanofibres for a wide range of biomedical applications such as cardiovascular implants, scaffolds for tissue engineering, repair of articulate cartilage, vascular grafts, urethral catheters, mammary prostheses, penile prostheses, adhesion barriers, and artificial skin (Giri *et al.* 2013; Cherian *et al*. 2010). In another interesting work, researchers reported that thermal stable nanocellulose from banana, jute, and PALF fibres can be used for various advanced nanotechnological applications (Abraham *et al.* 2011). Researchers obtained cellulose nanofibers from flax bast fibers, hemp fibers, kraft pulp, and rutabaga and developed nanocomposites from cellulose nanofibres which can find application in the medical field such as blood bags, cardiac devices, and valves as reinforcing biomaterials (Bhatnagar 2005). Kalia *et al.* (2011) have reviewed the processing methods, properties, and biomedical applications of nanocellulose and cellulosic composites. Also Eichhorn *et al.* (2009) reviewed recent progress made in the area of cellulose nanofibre-based nanocomposites and their application. Table 6 summarizes some patent regarding application of natural fibre for biomedical applications.

Biocompatibility

Biocompatibility is generally defined as the ability of a biomaterial to perform with an appropriate host response in a specific application. Several issues must be considered regarding the biological and host response to design biomedical biocomposites and predicting their performance (Hutmacher *et al.* 2000). As the number of constituent materials in composite increases, so can the variations in the host response. Different *in vitro* and *in vivo* tests are necessary to establish that the individual materials by themselves be biocompatible. Also, additional tests are required to ensure that their specific composition, arrangement, and interaction are biocompatible too.

Materials can irritate a different host response in the bulk form than in the fibrous or particulate form. For instance, an acetabular cup of a hip prosthesis, is generally biocompatible, whereas its fibrous form, as in a finely woven fabric, has been shown to produce a different, more adverse reaction (Patel and Gohil 2012). Moreover, in orthopedic or dental composites, friction in a moving part can scrape the matrix and expose the reinforcing material to the host and produce new challenges at the interface.

Table 6. Published Patents for Biomedical Applications of Natural Fibre

No.	Patent No.	Title	Year
1	WO/2013/148399	Medical balloon with incorporated fibres	(Aggerholm *et al*. 2013)
2	CN102715804	Polyester cool-fibre antibacterial pillow	(Mao 2012)
3	CN102715983	Medical natural porous fiber filler and vacuum sealing drainage device thereof	(Xiang *et al.* 2012)
4	CN102677504	Manufacturing process of antibacterial bamboo pulp used for high-wet-modulus fibre	(Xue *et al*. 2012)
5	CN102665510 -	Flushable moist wipe or hygiene tissue	(Strandqvist 2012)
6	CN101703317	Far-infrared fibre fabric functional bellyband by utilizing nano selenium, germanium and zinc elements traditional Chinese medicine	(Cheng & Cheng 2010)
7	US20090234459	Medical device for insertion into a joint	((Lund *et al.* 2008))
8	EU1896088	Medical device for insertion into a joint	(Lund *et al.* 2008)
9	CN1609336	Antiviral fibre and producing method and use thereof	(Zhou & Wu 2006)
10	CA2437616	Manufacturing of nano-fibres, from natural fibres, agro based fibres and root fibres	(Sain & Bhatnagar 2005)
11	CN461827	Natural antibacterial material and its use	(Yu 2003)
12	WO/2002/054998	Absorbable protective coatings for wound with the use of sponge and process for producing the same	(Taniguchi *et al.* 2006)
13	EP0818184	Medical prosthesis, especially for aneurysms, with a connection between its liner and its structure	(Cottenceau *et al.* 1998)

The interaction of materials at the interface is essential to composite performance, and this can be affected by the tissue response in various ways. As biomedical application of natural fibre and biocomposite is a new field, most of the research has focused on improving properties of natural fibre and also enhancement properties between the polymer matrices and natural fillers in order to improve the physical and mechanical properties of the end products. Novel and innovative approaches in the *in vitro* and *in vivo* tissue compatibility of this biomaterial product must be developed to address these significant issues.

CLOSING STATEMENTS

Development of biocomposites by using natural fibres as an alternative to petroleum based materials would help to reduce dependence on imported oil, carbon dioxide emission, and help to generate more economical opportunities for the agricultural sector. Furthermore, biocomposites offer opportunities for environmental gains, reduced energy consumption, insulation, and sound absorption properties. Nowadays, the use of biocomposites in biomedical applications offers several advantageous characteristics such as being low cost, lightweight, environmentally friendly, bio-renewable, and more durable. However, they have some disadvantages as well, such as moisture absorption and photochemical degradation because of the UV radiations. In this regard, there is ongoing research to address these issues.

Human bone and tissue are essentially composite materials having anisotropic properties. The anisotropy of the elastic properties of the biological tissues has to be considered in the design criterion for implants made from composite biomaterials. The solution to this is a new porous resorbable ceramic-polymer biocomposite, with morphology and a mechanical resistance similar to those of natural cancellous bone. Moreover surgeons can easily cut the graft directly in the surgery room to adapt its shape to the defect. Since they offer both low elastic modulus and high strength, they have been proposed for several orthopedic applications. Also, by controlling the percentage of the reinforcing and continuous phase, the properties and design of the implant can be tailored to suit the mechanical and physiological conditions of the host tissues. Moreover, problems of corrosion and release of allergenic metal ions, such as nickel or chromium, are totally eliminated. The composite provides high fracture toughness and high resistance against fatigue failure. These biocomposites are highly compatible with modern diagnostic methods, such as computed tomography (CT) and magnetic resonance imaging (MRI) as they show very low X–Ray scattering and their magnetic susceptibility is very close to that of human tissue. Also, they are lightweight. For some applications as in dental implants, biopolymers offer a better aesthetic characteristic. The cost of production of these implants is generally low, but the production process may be highly sophisticated. Biocomposites are used for hard tissue applications, including prosthetic socket, dental post, external fixator, bone plate, orthodontic archwire, orthodontic bracket, total hip replacement, and composite screws and pins. An example of the use of biocomposites in clinical application is cages for spinal fusion. Benefits for patients are a faster bone healing, no risk of pathogen transfer compared to allograft, faster and cheaper surgery, and less pain compared to auto graft.

REFERENCES CITED

Abraham, E., Deepa, L. A., Pothan, M., Jacob, S., Thomas, U., Cvelbar, R., and Anandjiwala. (2011). "Extraction of nanocellulose fibrils from lignocellulosic fibres: A novel approach," *Carbohydrate Polymers* 86(4), 1468-1475.

Aggerholm, S., Bodewadt, T., and Lysgaard, T. (2013). "Medical balloon with incorporated fibres," WIPO patent WO/2013/148399.

Ambrose, C. G., and Clanton, T. O. (2004). "Bioabsorbable implants: Review of clinical experience in orthopedic surgery," *Annals of Biomedical Engineering* 32(1), 171-177, Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14964733

Asokan, P., Firdoous, M., and Sonal, W. (2012a). "Properties and potential of bio fibres, bio binders, and bio composits," *Rev. Adv. Mater. Sci*. 30, 254-261.

Asokan, P., Firdoous, M., and Sonal, W. (2012b). "Properties and potential of biobinders, and biocomposites," *Rev. Adv. Mater. Sci*. 30, 254-261. Retrieved from http://mp.ipme.ru/e-journals/RAMS/no_33012/04_asokan.pdf

Barthelat, F. (2007). "Biomimetics for next generation materials," *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* 365(1861), 2907-2919. doi:10.1098/rsta.2007.0006

Bhatnagar, A. (2005). "Processing of cellulose nanofiber-reinforced composites," *Journal of Reinforced Plastics and Composites* 24(12), 1259-1268, doi:10.1177/0731684405049864

Biagiotti, J., Puglia, D., and Kenny, J. M. (2004). "A review on natural fibre-based composites - Part I.," *Natural Fibre* 1(2), 37-68.

Bledzki, A., and Jaszkiewicz, A. (2010). "Mechanical performance of biocomposites based on PLA and PHBV reinforced with natural fibres – A comparative study to PP," *Composites Science and Technology* 70(12), 1-37. Retrieved from http://www.sciencedirect.com/science/article/pii/S0266353810002319

Bodros, E., Pillin, I., Montrelay, N., and Baley, C. (2007). "Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications?" *Composites Science and Technology* 67(3-4), 462-470.

Chandramohan, D., and Marimuthu, K. (2011). "Characterization of natural fibers and their application in bone grafting substitutes," *Acta of Bioengineering and Biomechanics / Wrocław University of Technology* 13(1), 77-84. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/21500767

Cheng, G., and Cheng, J. (2010). "Far-infrared fibre fabric functional bellyband by utilizing nano selenium, germanium and zinc elements traditional Chinese medicine," China Patent CN101703317.

Cherian, B., Leao, A., Souza, D., Thomas, S., and Pothan, L. (2010). "Isolation of nanocellulose from pineapple leaf fibres by steam explosion," *Carbohydrate Polymers* 81(3), 720-725.

Cheung, H., Ho, M., Lau, K., Cardona, F., and Hui, D. (2009). "Natural fibre-reinforced composites for bioengineering and environmental engineering applications," *Composites Part B: Engineering* 40(7), 655-663. doi:10.1016/j.compositesb.2009.04.014

Corbie, T. (2001). "Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics," 33, 267-287.

Cottenceau, J. P., Nadul, G., Chevillon, G., and Roussigne, M. (1998). "Medical prosthesis, especially for aneurysms, with a connection between its liner and its structure," European Patent EP0818184
Cullen, R. K., Singh, M. M., and Summerscales, J. (2013). "Characterisation of natural fibre reinforcements and composites," *Journal of Composites* 2013, 1-4. doi:10.1155/2013/416501.
Czaja, W. K., Young, D. J., Kawecki, M., and Brown, R. M. (2007). "The future prospects of microbial cellulose in biomedical applications," *Biomacromolecules* 8(1), 1-12. doi:10.1021/bm060620d
Daunton, C., and Kothari, S. (2012). "A history of materials and practices for wound management," *Wound Management* 20(4). Retrieved from http://search.informit.com.au/documentSummary;dn=058025628512911;res=IELHEA
Dhandayuthapani, B., Yoshida, Y., Maekawa, T., and Kumar, D. S. (2011). "Polymeric scaffolds in tissue engineering application: A review," *International Journal of Polymer Science* 2011(ii), 1-19. doi:10.1155/2011/290602
DiGregorio, B. E. (2009). "Biobased performance bioplastic: Mirel," *Chemistry & Biology* 16(1), 1-2. doi:10.1016/j.chembiol.2009.01.001.
Eichhorn, S. J., Dufresne, A., Aranguren, M., Marcovich, N. E., Capadona, J. R., Rowan, S. J., and Peijs, T. (2009). "Review: Current international research into cellulose nanofibres and nanocomposites," *Journal of Materials Science* 45(1), 1-33.
Everitt, N. M., Aboulkhair, N. T., and Clifford, M. J. (2013). "Looking for links between natural fibres' structures and their physical properties," *Conference Papers in Materials Science*, 1-10. doi:10.1155/2013/141204.
Flory, A., and Requesens, D. (2013). "Development of a green binder system for paper products," *BMC*, Retrieved from http://www.biomedcentral.com/content/pdf/1472-6750-13-28.pdf
Garcia, M. I., and Garmendia, J. G. (2007). "Influence of natural fiber type in eco-composites," *Journal of Applied Polymer Science* 107, 2994-3004.
Giri, J., Adhikari, R., and Campus, T. (2013). "A brief review on extraction of nanocellulose and its application," *Nepal Journals OnLine* 9, 81-87.
Goldstein, S. A, Matthews, L. S., Kuhn, J. L., and Hollister, S. J. (1991). "Trabecular bone remodeling: An experimental model," *Journal of Biomechanics*, 24(Suppl. 1), 135-150. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1791174
Hin, T. S. (2004). *Engineering Materials for Biomedical Applications* (Vol. 1). World Scientific. doi:10.1142/5673
Hutmacher, D., Hürzeler, M. B., and Schliephake, H. (2000). "A review of material properties of biodegradable and bioresorbable polymers and devices for GTR and GBR applications," *The International Journal of Oral & Maxillofacial Implants* 11(5), 667-678. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8908867
Jawaid, M., and Abdul Khalil, H. P. S. (2011). "Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review," *Carbohydrate Polymers* 86(1), 1-18. doi:10.1016/j.carbpol.2011.04.043
Joshi, S., Drzal, L., Mohanty, A., and Arora, S. (2004). "Are natural fiber composites environmentally superior to glass fiber reinforced composites?" *Composites Part A: Applied Science and Manufacturing* 35(3), 371-376. doi:10.1016/j.compositesa.2003.09.016
Kabir, M., and Wang, H. (2011). "Effects of natural fibre surface on composite properties: A review," Proceedings of the 1st International Postgraduate Conference

on Engineering, Designing and Developing the Built Environment for Sustainable Wellbeing, Retrieved from http://eprints.usq.edu.au/18822
Kalia, S., Dufresne, A., Cherian, B. M., Kaith, B. S., Avérous, L., Njuguna, J., and Nassiopoulos, E. (2011). "Cellulose-based bio- and nanocomposites: A review," *International Journal of Polymer Science.* Volume 2011, Article ID 837875, 35 pages. *doi:10.1155/2011/837875*.
Kalia, S., Kaith, B., and Kaur, I. (2009). "Pretreatments of natural fibers and their application as reinforcing material in polymer composites—A review," *Polymer Engineering & Science* 49(7), 1253-1272. doi:10.1002/pen
Kutz, M., Adrezin, R., and Barr, R. (2003). *Standard Handbook of Biomedical Engineering and Design* (pp. 1-17). Retrieved from http://www.pessoal.utfpr.edu.br/pichorim/AULA/Bioengenharia/Kutz_Biomed_17.pdf
Lund, S. S., Ole, O., Bruun, L. J., Logstrup, A. T., Povl, B., Klaus, B., and Kristoffer, A. (2008). "Mouritsen Soren medical device for insertion into a joint," U.S Patent US20090234459.
Majeed, K., Jawaid, M., Hassan, A., Abu Bakar, A., Abdul Khalil, H. P. S., Salema, A. A., and Inuwa, I. (2013). "Potential materials for food packaging from nanoclay/natural fibres filled hybrid composites," *Materials & Design* 46, 391-410. doi:10.1016/j.matdes.2012.10.044
Mao, Z. (2012). "Polyester cool-fibre antibacterial pillow," China Patent CN102715804
Meyers, M. A., Chen, P.-Y., Lin, A. Y.-M., and Seki, Y. (2008). "Biological materials: Structure and mechanical properties," *Progress in Materials Science* 53(1), 1-206. doi:10.1016/j.pmatsci.2007.05.002
Milanese, A. C., Cioffi, M. O. H., and Voorwald, H. J. C. (2011). "Mechanical behavior of natural fiber composites," *Procedia Engineering* 10, 2022-2027. doi:10.1016/j.proeng.2011.04.335
Mohanty, A. K., Misra, M., and Drzal, L. (2002). "Sustainable bio-composites from renewable resources: Opportunities and challenges in the green materials world," *Journal of Polymers and the Environment* 10(1-2), 18-26.
Morgan, C., and Nigam, Y. (2013). "Naturally derived factors and their role in the promotion of angiogenesis for the healing of chronic wounds," *Angiogenesis* 16(3), 493-502. doi:10.1007/s10456-013-9341-1
Mueller, D., and Krobjilowski, A. (2004). "Improving the impact strength of natural fiber reinforced composites by specifically designed material and process parameters," *Int. Nonwovens J.* 13(4), 31-38. Retrieved from http://www.jeffjournal.org/INJ/inj04_4/p31-38t-mueller.pdf
Mukhopadhyay, S., and Fangueiro, R. (2009). "Physical modification of natural fibers and thermoplastic films for composites -- A review," *Journal of Thermoplastic Composite Materials* 22(2), 135-162. doi:10.1177/0892705708091860
Navarro, M., Michiardi, A., Castaño, O., and Planell, J. A. (2008). "Biomaterials in orthopaedics," *Journal of the Royal Society, Interface / the Royal Society* 5(27), 1137-1158. doi:10.1098/rsif.2008.0151
Oksman, K., Skrifvars, M., Selin, J-F. (2003). "Natural fibres as reinforcement in polylactic acid (PLA) composites," *Composites Science and Technology* 63, 1317–1324.
Patel, N. R., and Gohil, P. P. (2012). "A review on biomaterials: Scope, applications & human anatomy significance," *International Journal of Emerging Technology and Advanced Engineering* 2(4), 91-101.

Puglia, D., Biagiotti, J., and Kenny, J. (2005a). "A review on natural fibre-based composites—Part II: Application of natural reinforcements in composite materials for automotive industry," *Journal of Natural Fibers* 1(3). Retrieved from http://www.tandfonline.com/doi/abs/10.1300/J395v01n03_03

Puglia, D., Biagiotti, J., and Kenny, J. (2005b). "A review on natural fibre-based composites—Part II: Application of natural reinforcements in composite materials for automotive industry," *Journal of Natural Fibers* 1(3). Retrieved from http://www.tandfonline.com/doi/abs/10.1300/J395v01n03_03

Ramakrishna, S., Mayer, J., Wintermantel, E., and Leong, K. W. (2001). "Biomedical applications of polymer-composite materials: A review," *Composites Science and Technology* 61, 1189-1224.

Ratner, B., and Hoffman, A. (2004). *Biomaterials Science: A Multidisciplinary Endeavor*, Google eBook, Academic Press. Retrieved from http://www.elsevierdirect.com/companions/9780125824637/samplechapters/ch01.pdf

Romanzini, D., Luiz, H., Junior, O., Campos, S., and José, A. (2012). "Preparation and characterization of ramie-glass fiber reinforced polymer matrix hybrid composites. 2 . Experimental procedures," 15(3), 415-420.

Sain, M., and Bhatnagar, A. (2005). "Manufacturing of nano-fibres, from natural fibres, agro based fibres and root fibres," patent CA2437616.

Sarasini, F., Puglia, D., Fortunati, E., Kenny, J. M., and Santulli, C. (2013). "Effect of fiber surface treatments on thermo-mechanical behavior of poly(lactic acid)/phormium tenax composites," *Journal of Polymers and the Environment* 21(3), 881-891. doi:10.1007/s10924-013-0594-y

Strandqvist, M. (2012). "Flushable moist wipe or hygiene tissue," patent CN102665510

Taniguchi, K., Kohno, I., Tanabe, K., Jo, Y., and Ohnishi, I. (JP). (2006). "Absorbable protective coatings for wound with the use of sponge and process for producing the same," WIPO patent WO/2002/054998.

Teoh, S. (2000). "Fatigue of biomaterials: A review," *International Journal of Fatigue* 22(10), 825-837. doi:10.1016/S0142-1123(00)00052-9

Ticoalu, A. (2010). "A review of current development in natural fiber composites for structural and infrastructure applications," Proceedings of the Southern Region Engineering Conference 2010. Retrieved from http://eprints.usq.edu.au/9253

Verma, D., Gope, P., and Shandilya, A. (2013). "Coir fibre reinforcement and application in polymer composites: A review," *J. Mater. Environ. Sci.* 4(2), 263-276. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Coir+Fibre+Reinforcement+and+Application+in+Polymer+Composites+:+A+Review#4

Wu, T.-M., and Wu, C.-Y. (2006). "Biodegradable poly(lactic acid)/chitosan-modified montmorillonite nanocomposites: Preparation and characterization," *Polymer Degradation and Stability* 91(9), 2198-2204. doi:10.1016/j.polymdegradstab.2006.01.004

Xiang, Q., Guofeng, X., Juan, D. U., and Xie, W. (2012). "Medical natural porous fiber filler and vacuum sealing drainage device thereof," China Patent CN102715983.

Xue, Q., Xu, F., Yu, W., Liu , A., Pu, Y., and Zhang, L. (2012). "Manufacturing process of antibacterial bamboo pulp used for high-wet-modulus fibre," China Patent CN102677504

Yang, H.-S., Wolcott, M. P., Kim, H.-S., Kim, S., and Kim, H.-J. (2006). "Properties of lignocellulosic material filled polypropylene bio-composites made with different manufacturing processes," *Polymer Testing* 25(5), 668-676. doi:10.1016/j.polymertesting.2006.03.013

Yu, G. (2003). "Natural antibacterial material and its use," China Patent CN1461827.

Zainudin, E., and Sapuan, S. (2009). "Mechanical properties of natural fibre reinforced PVC composites: A review," *Sains Malaysiana* 38(4), 531-535. Retrieved from http://journalarticle.ukm.my/45/

Zhou, S., and Wu, Z. (2006). "Antiviral fibre and producing method and use thereof," China Patent CN1609336.

Zhu, J., Zhu, H., Njuguna, J., and Abhyankar, H. (2013). "Recent development of flax fibres and their reinforced composites based on different polymeric matrices," *Materials* 6(11), 5171-5198. doi:10.3390/ma6115171

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