Journal of Bionic Engineering (2022) 19:1562–1577
https://doi.org/10.1007/s42235-022-00240-x

REVIEW ARTICLE

Biopolymers and Biomimetic Materials in Medical and Electronic-Related Applications for Environment–Health–Development Nexus: Systematic Review

Faris Mohammed AL-Oqla[1] · **Mohammed Hassouna Alaaeddin**[2] · **Muhammad Enamul Hoque**[3] · **Vijay Kumar Thakur**[4,5]

Received: 20 April 2022 / Revised: 6 July 2022 / Accepted: 11 July 2022 / Published online: 13 September 2022

Abstract
Biocomposites as bio-inspired materials are produced from renewable resources that are organic and ecofriendly alternative materials. To improve the lifestyle of human beings as well as enhancing the environmental indices, functional bio-materials are now implemented in various promising industries. This work has systematically discussed and highlighted the implementations and trends of functional bionic materials in high tech industries, which are necessary for developing modern societies. Various medical, electronic, food and pharmaceutical applications have been considered. Bio-inspired materials are used to develop more sustainable possibilities to increase environmental conservation while maintaining customer satisfaction. Biopolymers were found employed in several sectors for various functional bio-products including organic thin-film transistors, organic phototransistor, emitting diodes, photodiodes, photovoltaic solar cells, hybrid dental resins, sustainable pharmaceuticals, and food packaging. They are used to create sustainable bio-products for energy storage and harvesting, bone regeneration, nerve damage repair, drug applications and various other industrial subcategories.

Keywords Biopolymers · Bioinspired · Biomimetic materials · Tissue engineering · Nerve repair · Organic transistors

1 Introduction

Producing renewable greener plastic composites will be more ecological for the modern societies. This can be achieved by using biotechnology and nanotechnology, which are promising approaches that would, to a great extent, impact the value chain of the plastic industry worldwide. However, procedures and further achievements have been carried out to develop potential plastics. Composite materials have been used thousands of years ago in all aspects of life. These materials generally consist of two components: the matrix that surrounds the reinforcement (most commonly, ceramics, metals, and polymers) and the reinforcement for enhancing the matrix. There are numerous types of composites such as carbon-reinforced fiber plastic, metal-matrix, carbon nanotube, and biomaterials [1–3]. Composites are essentially applied in various industries. However, green composites are increasingly needed for greener products [4–8].

A polymer is a big macromolecule with a high to extremely high molecular weight that is made up of multiple repeating units known as monomers that are covalently

---

✉ Faris Mohammed AL-Oqla
fmaloqla@hu.edu.jo

Mohammed Hassouna Alaaeddin
alaaeddin.sj@fairview.edu.my

Muhammad Enamul Hoque
enamul1973@bme.mist.ac.bd

Vijay Kumar Thakur
vijay.thakur@sruc.ac.uk

[1] Department of Mechanical Engineering, Faculty of Engineering, The Hashemite University, P.O Box 330127, Zarqa 13133, Jordan

[2] University College Fairview, 2A, Jalan TP2, Sime UEP Industrial Park Subang Jaya , 47600 Subang Jaya, Selangor, Malaysia

[3] Department of Biomedical Engineering, Military Institute of Science and Technology (MIST), Mirpur Cantonment, Dhaka 1216, Bangladesh

[4] Biorefining and Advanced Materials Research Center, Scotland's Rural College (SRUC), Kings Buildings, Edinburgh EH9 3JG, UK

[5] School of Engineering, University of Petroleum & Energy Studies (UPES), Dehradun 248007, Uttarakhand, India

bonded to one another. Monomers are frequently joined together in a row, much like links in a chain. However, chain branching and cross-linking do occur. Monomers can even be linked together to form a two-dimensional or three-dimensional polymer network. They are currently utilized for the natural fiber composites in various applications [3]. Protein is the primary component of both human and animal bodies. Proteins are polymers as well, with repeating units of amino acids joined together by peptide bonds. Generally, a polymer is categorized as either a homopolymer, which contains only one kind of monomer, or a copolymer, which has multiple types of monomers. A chemical reaction termed polymerization happens to form polymers from monomers. Polymers have been widely used in practical approaches for many years as they are adaptable materials that can be easily shaped to fit several applications. Thermoplastic and thermosetting resins have been commonly applied as the matrix in polymer composites.

Due to their fast microorganisms' degradation, biopolymers are of paramount importance for producing degradable products. Biodegradable polymers can be as either bio-based like Polylactic Acid (PLA) chitin, Polyhydroxyalkanoates (PHA), starch, chitosan Polybutylene Succinate (PBS), protein, and cellulosics) or petroleum-based like Poly(Butylene Adipate-co-Terephthalate (PBAT), Polycaprolactone (PCL), and Poly (Vinyl Alcohol) (PVOH). Such eco-friendly materials can be made from plant origins like starches of sugar palm, cassava, yam bean, corn, potato, as well as others [9]. Some of the main characteristics and advantages of such biomaterials are their ability to be broken down by naturally-occurring microorganism, not releasing harmful products after disposal, can be mixed with conventional plastics, have the ability to reduce greenhouse gas emission levels, and they usually use low energy during the production cycle. However, certain procedures with specific environmental conditions are required to dispose the biopolymer waste including certain levels of UV light, temperature and humidity. Moreover, their costs are relatively high as the costs of pesticides have to be considered during the manufacturing processes and they may produce methane during landfills.

Green composite materials are now commonly used in automobiles, lighting products, as well as medicinal and electronic applications [10–13]. Natural fiber-coated conductive materials are the subject of ongoing research. They can be enhanced for allowing pressure sensors to detect movements of wounded muscles and bones. Natural fibers have a high thermal tolerance. In construction materials reinforcements, natural fiber can be further investigated to minimize the use of glass fibers [11, 14–18]. Due to its cost efficiency and environmental advantages, natural fibers can replace synthetic materials and carbon fibers. This will also open the door for new jobs and will alter the way synthetic materials are being used [19–21].

With a balanced amount of catalysts and antioxidants, photodegradable plastics as bionic materials have been developed [22–24]. While maintaining the performance properties of plastics by catalysts, they also initiate a controlled degradation. Photodegradable plastics possess similar properties as common plastics and mostly at similar costs. Composites have infiltrated our daily lives and reached a high-level of application. They are used by numerous industries such as medical equipment, constructions, transportation, aerospace, sports, as well as oil and gas production [25–28]. The use of biopolymers as replacements to synthetic substances is steadily growing. Biopolymers have been employed within several industries such as tissue engineering and food packaging materials, applied science, and drug applications as they possess numerous benefits compared to synthetic counterparts. This has prompted researchers to investigate the valuable traits of such substances [29–32]. In fact, plenty of investigations are being conducted on biopolymer-based composites since artificial materials are costly, hazardous to the environment, and detrimental to the economy. Thus, efforts are being made to find out reliable solutions for the long term use of biopolymer-based composites since they have plenty of fascinating and useful properties such as high mechanical features, renewability, reasonable strength, low cost, low density and biodegradability features [26, 33, 34].

2 Biopolymers for Industry

Biopolymer physicochemical and thermomechanical characteristics are influenced by different factors such as biopolymer blend, reinforcement processes and plasticizers. Plasticizers are known as liquids with a high boiling point and molecular weight containing both linear and cyclic carbon chains [35–37]. The chemical structure determines the degree of plasticity of biopolymers. Biopolymer deterioration is influenced by a number of factors, including structure, atmosphere, polymer form, and chemical bonds. The following is a breakdown of the degradation process: Biodegradable: The existence of microorganisms causes degradation. Hydro-biodegradable: Degradation occurs when microorganisms and water are present. Photodegradable: Bioerodible: Degradation is caused by natural abrasion erosion. Delinking process between molecules takes place in the presence of light. Compostable: Microbial activity causes decomposition, which enhances soil conditions. Processing biopolymer plasticizers is essential. The plasticizer and biopolymer compatibility is a serious issue, which is influenced by different factors, e.g., polarization, dielectric constant, hydrogen bonding and solubility [38–41]. Plasticizers are often used as manufacturing additives due to their advantages in facilitating filler dispersion, reducing viscosity and temperature rise, facilitate movement, improve release, and enhance building efficiency.

Several types of biopolymers are being utilized in various industrial applications. The main types are the following:

2.1 Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates are degradable polyesters naturally synthesized by microorganisms, including bacterial fermentation of lipids and sugars. This type of biopolymers has good mechanical, biodegradability, and thermal processing characteristics. It can be used in agricultural, biomedical as well as packaging applications. It demonstrates good degradation behavior when buried in soil. For instance, it was shown experimentally 0.07-mm-thick PHA films could be degraded in about 6 weeks [24]. Since PHA are biocompatible and not destructive to living tissue, they are used in therapeutic, wearable and surgical applications. PHA, moreover, have the ability to decrease the landfill space required for bury the plastic waste due to the fast reliable biodegradability characteristics, which can reduce the environmental consequences. As bacterial plastics have gained interest worldwide, biopolymers are being utilized in various applications as they can be naturally degraded by such types of bacteria. The applications include skin care, medical devices, personal hygiene products and plastic packaging. Thus, the application of PHA is not only limited to bioplastics; PHA have also been utilized in making implantable biomaterials, fine chemicals, biofuels, medicine, and for regulating bacterial metabolism for better quality of industrial microorganisms. PHA are also utilized in tissue engineering including scaffold due to their biocompatibility characteristics, nontoxicity and the ability to support cell growth [42]. Additionally, PHA is utilized in controlled drug releasing systems. This is due to its capability to work with a suitable host response and biodegradability properties. Various monomers can also be added into PHA to enhance its physical characteristics resulting in a wide range of properties from strong elastomers to highly crystalline materials. The application of PHA can be also found in the electronics. This is due to the piezoelectric nature of PHA. Shock wave sensors, gas lighters, stretch and acceleration measuring instruments, pressure sensors, headphones, oscillators, ultrasonic detectors, loudspeakers, are some of the electronic components or parts that can be produced by PHA.

2.2 Starch

In its natural state, starch is different from thermoplastics and cannot be melted or treated similarly. Starches are usually semi-crystalline with about 20–45% crystallinity. Thermoplasticization of starch granules is usually achieved by heating and shearing process which takes place in the presence of glycerol or water [43, 44]. Moisture sensitivity, low strength and brittleness attributed to retrogradation are some of the drawbacks of thermoplastic starch (TPS). Mixing TPS with synthetic or biodegradable polymers will solve this issue [45, 46]. Figure 1 demonstrates a schematic representation of the chemical structures of both amylose starch and amylopectin starch.

Starch-based biopolymer films are mainly utilized in medicine such as capsules, candy wrappers and food packaging applications. Starch-based biopolymer films are also used for controlling water permeability. It is usually used as a barrier for volatile compounds and gases so that to maintain food freshness. But, with high water vapor permeability, starch-based biopolymer demonstrates some mechanical properties deterioration. Such material is normally stored in plants tissues as one-way of carbohydrates. However, it is not found in animal tissues. Starch has several advantages including being renewable, available, biodegradability, and cheap. Starch-based biopolymer has high degradation rates but with limited mechanical properties. It has several applications including pharmaceutical, food packaging biomedical, paper, horticulture, agriculture, and automotive ones. Molecular weight, functional groups and chemical makeup are all factors to consider [9, 47–49]. Thermoplastic starch is a semi-crystalline amorphous substance composed of gelatinized starch and one or more plasticizer(s). Amylopectin and amylose are the two main components of starch.

2.3 Protein

Protein is one of the most abundant biological macromolecules in cells with wide variety of species and sizes. It is mainly used for producing protein films. However, it is used to provide bioactive properties after improving their performance. Various types of animal protein are usually utilized including caseins, collagen, egg proteins, gelatin, and myofibrillar proteins. However, soy protein, gluten and zein are among the vegetable most used proteins. Protein biopolymer has several advantages for food packaging including the highly nutritional quality, protecting food products from surroundings, and the excellent sensory properties [50, 51]. Protein films have good polymeric features that enable them to be implemented for edible food packaging application. Proteins-based bio-compatible biomaterials have been utilized to improve scaffolds for many biomedical applications like that of tissue engineering, drug delivery, wound dressings, and membrane filters.

Soy protein contains 18 amino acids with 60% usable functional groups [51–54]. By utilizing hydrogen bonding, polar hydrophilic bonding and charge-charge interactions, it can easily trap airborne contaminants. Positively charged NH_3 in chitosan-based air filters deactivates E.coli gram-negative bacteria. Hence, they are being used as possible

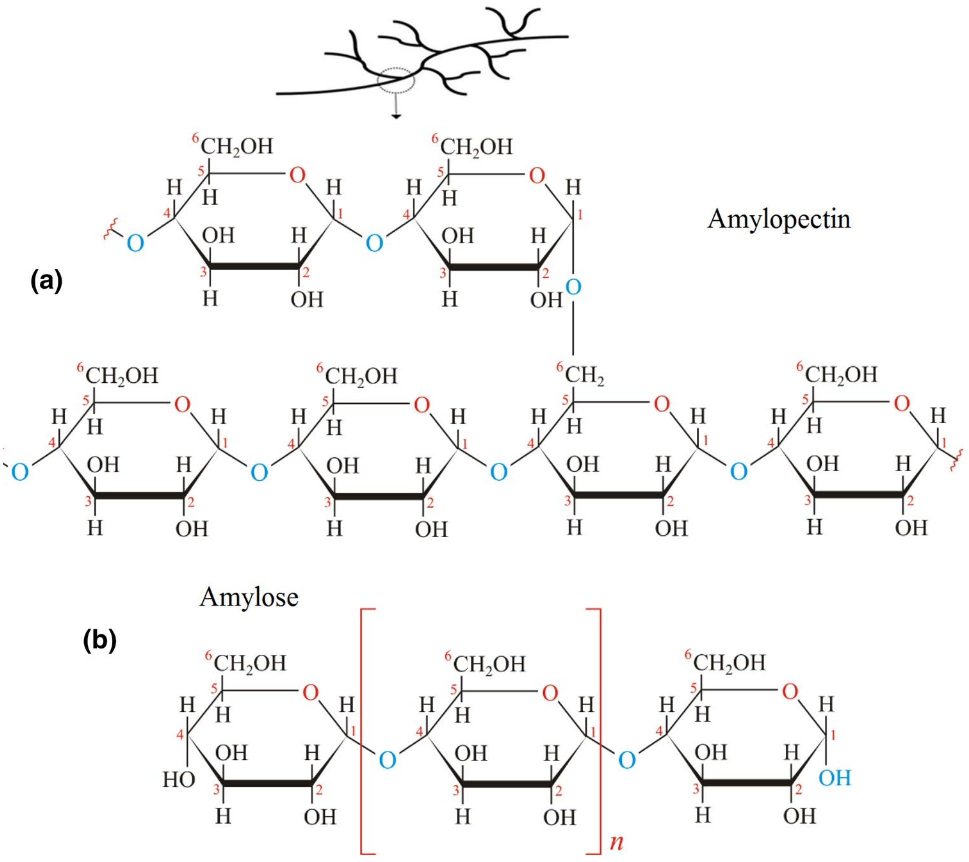


Fig. 1 A graphic representation of the chemical structures of (**a**) amylopectin starch and (**b**) amylose starch

bacterial filters [55]. Biopolymers (such as collagen) are employed to create 3-dimensional and 2-dimensional electrospun nano-fibers for skin treatment and tissue recovery. Electrospun fibers have been created to treat wounds in addition to growth medicines such as fibroblast growth factor loaded with poly (ethylene imine [56]. The utilization of nano-fibers for treating dry wounds has several reported drawbacks. However, despite these drawbacks, it is still recommended as it dries out the wound and speeds up the healing process. Wheat gluten, Corn, Soy protein, Gelatin, Whey protein and Casein have also been used to create protein films. Low oxygen permeability is reported in Protein films. Owing to the hydrophobic properties of many of these proteins, protein films have greater water vapor permeability than plastic films, such as polyhydroxyalkanoates (PHA)-based packaging materials [57, 58]. Baked goods, cooked beef, cheese, and other foods are packaged with nitrocellulose wax or polyvinylidene chloride-coated cellophane. Protein films (such as plastic films) have low oxygen permeability, greater water vapor permeability and excellent film-forming capacity. Gluten-based composites can be rendered as fire-resistant using lanosol as an additive. According to findings, the fire retardancy effect was stronger even than traditional fire retardants such as tetrabromobisphenol A and hexabromocyclododecane. Lanosol slowed the ignition and reduced the amount of heat generated [59]. Gluten may also be treated with triethylene glycol and dialdehyde to create an antimicrobial composite. Biomedical devices use chitosan-based biopolymers coated on magnesium as well as chitosan-based antimicrobial bio-implants. For biomedical purposes, a novel source of biopolymers centered on sugar-derived polylactides has been created in the pharmaceutical industry. When they decay in the human body, they have no adverse side effects. In the food industry, genetically coded peptides such as poly peptides with recurring peptide signatures and poly amino acids can be used for many applications, e.g., protein purification and drug delivery. However, there are drawbacks such as the acidification process affecting the scale of biopolymer complexes and peptides becoming susceptible to oxidative deterioration. These limitations may be solved in future using a precise structural analysis with high affinity and structural stability. Genetically coded peptides can be made immune to oxidative and enzymatic deterioration to greatly enhance their attributes, especially the functional ones. In this regard, several peptide drugs, such as EP100 (Phase II), AEZS108 (Phase II) and NGR-hTNF (Phase III), are still in various stages of clinical trials. Biopolymers are commonly used in the biomedical, dairy, and pharmaceutical industries. It is asserted that perfluorosulfonic acid-based membranes were substituted by biopolymer chitosan-based membranes in the applications of fuel cells. They exhibited improved ion conductivity in anhydrous conditions. Ionic liquids and bio-based membranes are also strong long-term sources of renewable energy [54]. Because of their remarkable absorbance quality, air filters made of chitosan, cellulose and soy protein are similar to synthetic filter systems.

2.4 Polylactic Acid

There has been a remarkable increase in public awareness on the use of natural-based materials. Such awareness has influenced numerous scientific and manufacturing platforms. For instance, composite manufacturing now employs biodegradable and natural materials instead of synthetic and harmful materials. One of the most promising and widely used composite for reinforcing materials is polylactic acid (PLA). PLA is used in numerous applications as in Table 1. Its properties have been extensively investigated. Degradable plastics can reduce harmful environmental effects; therefore, PLA is a great alternative for curbing the buildup of toxic waste and nonbiodegradable materials. Other polymers can also be used to produce natural fiber composite-based materials that are either thermoset or thermoplastic. Thermoplastics are usually more preferable due to their remolding features and manufacturing merits [60–66]. Throughout the manufacturing process, PLA's properties can be tailored to change or lower the mass molecular weight and Glass Transition temperature (TG).

3 Biopolymer for Medical and Dentistry Applications

Biomaterials are usually utilized to make several functional products for the human being. Such functions are associated with either remediation like nerve repair, broken bones or functions that the body can't do anymore. Biomaterials roles are either to be supportive for the body to perform a certain function like that supporting the bone till it's healed, or fixing the tissue like nerve repair and implantable sensors. This is due to their biocompatibility with human body and non-toxicity features. Various biomaterials are being utilized as alternatives to bone grafts. Bio-components are also utilized as restorative materials and coupling agents and fillers for dentistry due to their reasonable flexural strength, higher filler content, and increased hardness. Low viscosity is reported in flowable composites, making them more fluid when compared to conventional composite resins. Their inorganic filler percentage is lower. Rheological modifiers aimed to improve handling properties have been removed from their composition. The high attributes of flowable composites such as high wettability on the tooth surface make a flawless penetration into irregularity, another attribute is the ability to maintain minimum thickness of layers and eliminates entrapment or air inclusion [68, 69]. They also possess high flexibility, providing them with less opportunity to be displaced in areas of concentrated stress (cavitated dentine areas and cervical wear processes). They further possess radio-opaqueness features and are available in different colors. However, their disadvantages are their high curing shrinkage caused by lower filler load and weaker mechanical properties.

In recent years, tissue engineering has aided in regenerating and repairing different types of tissues. Bone Tissue Engineering (BTE) is mainly composed of cells, scaffolds and growth factors. Numerous challenges are found in the development of BTE. Scaffolds are mainly applied throughout the processing method, and they are the main components of a material [70–72]. They can be flexibly shaped into various structures. Biopolymers are biocompatible with fixed rates of degradation, making them more efficient than artificial alternatives. However, they exhibit low mechanical properties such as decreased strength, which can be a considerable drawback. Bioactive polymers/ceramic composite scaffolds are mainly the combination of biopolymers with inorganic materials such as calcium phosphate [72, 73]. Another common method applied to produce BTE scaffolds is the integration of CaP into polymer matrices; this decreases the natural organic–inorganic composites. Examples of some integration methods include biomimetic mineralization, physical mixture, and chemical deposition[74]. For cell-based therapies, a suitable environment must be maintained to produce a living scaffold in tissue engineering [75].

Table 1 The applications and usages of PLA plastics [67]

Applications	Usages
Domestic	Cutlery, cups, plates, saucers, food products, food compartments, natural product juices, water bottles, sports drinks, cold beverage cups, edible-oils compartments, jam holders and dairy holders
Medical	Clinical gadgets like plates, screws, pins and bars
Packaging	Vegetable sacks, serving of mixed greens, candy wrappers, lid films, rankle bundling, envelope films, name film, bundling applications and shrivel wrappings
FDM machines	3D medical printings; either perpetual or biodegradable, 3D fiber modeling, lost-PLA casting

Figure 2 provides examples of biopolymers applications in different medical fields.

Biomaterials have been significantly used in ophthalmology, which considers to the diseases and medical conditions relating to the eye and determining the proper treatment. for instance, in ocular endotamponade, drug delivery systems, Glaucoma filtration implants, artificial lacrimal ducts, artificial orbital walls, Intraocular Lenses (IOLs), artificial corneas, retinal tacks and adhesives, scleral buckles, contact lenses, and viscoelastic replacements [10, 72]. High strength, fracture toughness, and hardness are properties of metals, the main materials utilized in orthopedic applications [14, 76]. A few polymers used in orthopedics include ultrahigh-molecular-weight polyethylene and poly (methyl methacrylate). Fixing nerve damage is a complicated physiological process. Nervous system is classified into two: the central nervous system (CNS) and the peripheral nervous system (PNS). Some methods used to repair the nervous system include transfer of therapeutics, cell transplantation with scaffolds and direction channels [77]. Figure 3 illustrates the application of bio-materials in nerve repair.

On the other hand, optical sensors for biomedical applications use light for the valuation of cells, skin tissue, and other samples. Optical fiber sensors offer exceptional competences for accurate assessment of biological tissues to demonstrate an advance in treating early disease diagnosis, and treatment-response monitoring. Biomaterials may be advantageous due to their biocompatibility as well as electromagnetic interference lack of restrictions, in addition to the flexibility in design that offers optimized tissue characterization. There are several types of biosensors available and used in so many individual devices. However, several

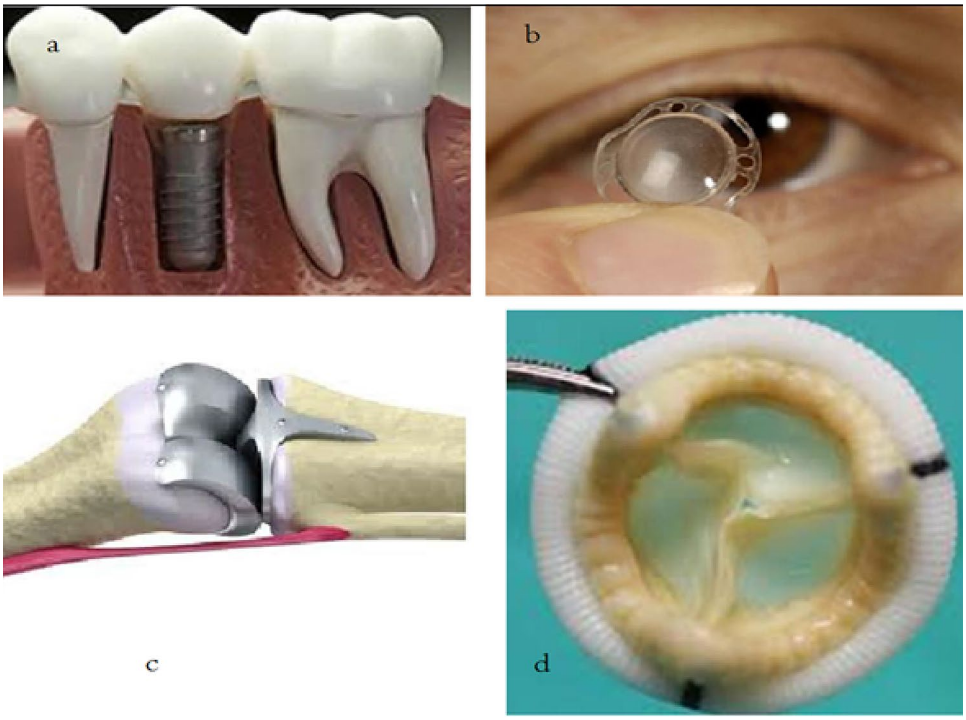


Fig. 2 Different medical applications of biopolymers (**a**) An endosteal dental implant (**b**) Artificial cornea implant (**c**) Knee artificial joint (**d**) Artificial heart valve [72]

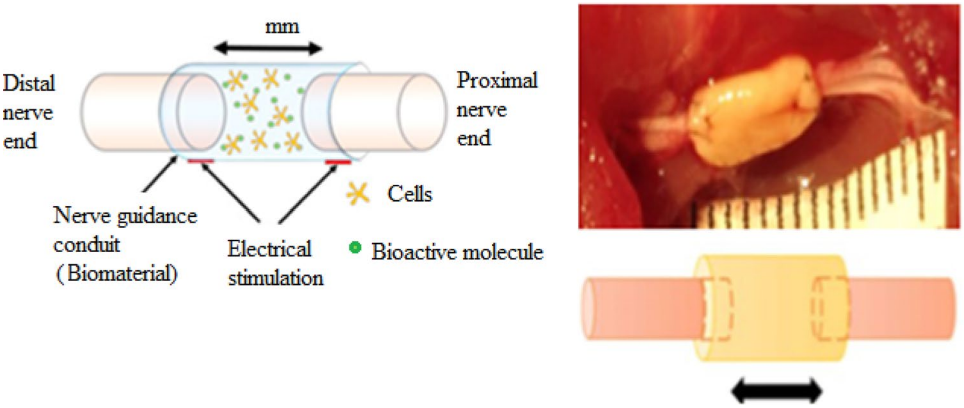


Fig. 3 A depiction of nerve damage repair involving biomaterials [78]

types of sensors are not user friendly as users may feel uncomfortable due to the sensors sizes and weights. Biomaterial based biosensors are thus possible solution to this, and have the possibility to be integrated with smart textile structures. This leads to generate new type of textiles that have more smart functions that provides attractive solutions for several applications including healthcare, automotive industry, sports, and clothing for protection.

Restorative material is an example of synthetic resins that have been used in dentistry. The main components of restorative materials are coupling agents, fillers (inorganic part), and the resin matrix (organic content). Composites with a round fillers shape are much better than pre-polymerized composite fillers due to greater flexural strength, higher filler content, and increased hardness. Composite resins can be classified in various ways depending on their composition. This was established to make the process more reliable for dentists to select and use composite resins for therapeutic purposes. One popular classification that is still valid today has been derived from Lutz and Phillips, who based their classification on filler particle size. These authors divided the composite resins into three categories: (i) Macro-filler composites (particles from 0.1 to 100 µm) (ii) Micro-filler composites (0.04 µm particles) (iii) Hybrid composites (different sized fillers). More detailed classification was introduced by Willems who based categorization on several parameters such as Young's module, size of main particles, percentage of inorganic filler (by volume), compressive stress, and surface roughness. The resin matrix mainly consists of Bi-phenol-A Glycidyldimethacrylate (Bis-GMA) [79, 80]. Since Bis-GMA is highly viscous, it is mixed in different combinations with short chain monomers such as Triethylene Glycol-dimethacrylate (TEGDMA). Fillers are commonly made of silica, quartz, and/or ceramic. When the filler content is increased, the polymerization shrinkage (i.e., water absorption and linear expansion coefficient) will decrease, whereas the compressive and tensile strength, modulus of elasticity and wear resistance will increase. These composites were named hybrid since they are composed of polymer groups (organic phase) and reinforced by an inorganic phase of glass fillers with different compositions/sizes, consisting of 60% or more of the total content. The particle size range is 0.6 to 1 µm, and they contain colloidal silica (0.04 µm in size). They represent most composites currently used in dentistry[80]. The main properties of these materials include: a wide range of colors to look similar to the dental structure, water absorption is very low with less curing shrinkage, polishing and texturing properties are excellent, abrasion and wear are very similar to the structure of teeth, and they match the thermal expansion coefficient of teeth.

Condensable composites have high filler percentage. Their advantages include condensability (like silver amalgam), easier to achieve a good contact point, and much better in occlusal anatomy reproduction. They behave mechanically and physically similar to silver amalgam and are better than hybrid composites[81]. However, according to follow-up studies, it was found that their clinical behavior is almost similar to that of hybrid composites[82]. Their disadvantages include difficulties to adapt one composite layer with another, complexity in handling, as well as poor aesthetics in anterior teeth. Numerous applications for modern composite materials are present in today's dentistry. Dental composites bond chemically with the tooth structure, resulting in structural strength. This thereby restores the original physical integrity of the tooth. Since composites are glued to the tooth, less healthy teeth should be removed for composite restoration process.

Since composite fillings are bonded or glued to the tooth, unlike amalgam fillings, it is not necessary to make retentive features that can destroy a healthy tooth [83, 84]. Figure 4 provides an example of bio-composites applications in dental filling and crowns and adhesive composite bridges. The durability of composite crowns is not like gold, porcelain, or zirconian crowns and therefore must be replaced more often. In specific situations, composite crowns can have a

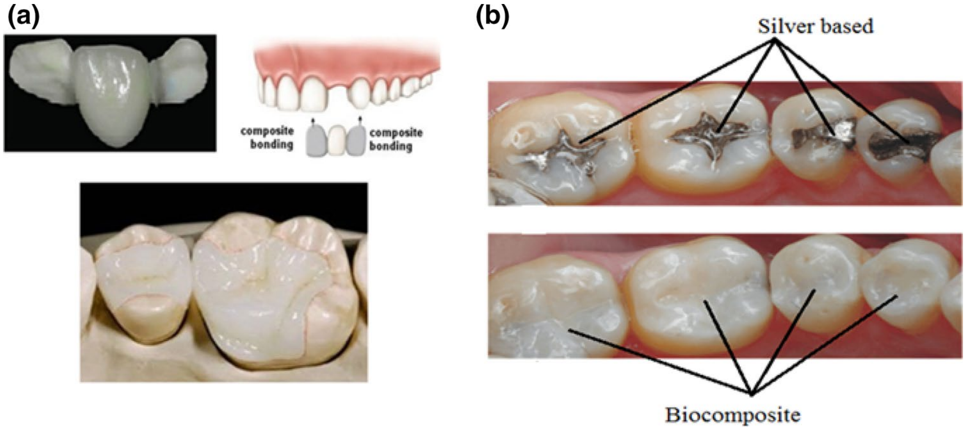


Fig. 4 Depictions of different dental composites, (**a**) Adhesive composite bridges, composite bonding, and dental composite inlays on the dental cast, (**b**) Metal filling, and a composite filling fully covers all sides of crowns for more aesthetic demands

metal shell. Metal composite crowns are usually made with a partial veneer covering only the visible parts of the crown. However, it is still possible to cover all sides of the crown with composites if aesthetic demands are high. Some of the indications are as follows: (i) Very rare; patients with metal hypersensitivity who are incapable of tolerating full porcelain (ii) Patients who cannot afford the costly types of crowns and (iii) Temporary/interim option for high decay-rate patients.

Composite inlays are indirect restorations, lab-made, which are bonded within the prepared tooth cavity to result in strengthening the entire tooth structure. Adhesive composite bridges are attaching a false composite tooth with neighboring teeth using a bonding procedure as shown in Fig. 4. There will be no grinding of neighboring teething in this case, making it a great advantage [85, 86].

When it comes to metal shells, composite dental bridges are similar to crowns, they can have a metal shell where the composite is commonly placed in the form of veneers. Metal composite bridges generally have a similar structure to crowns and are usually recommended when patients cannot afford more expensive solutions [85]. In some cases, composite bridges can be fiber-reinforced. In addition, a resin-bonded bridge functions better than a removable denture, but cannot replace fixed bridgework dental implants. Aesthetics are moreover used to reshape teeth and close the diastema between them, for instance, veneers; they are thin layers of material placed over a tooth. They can improve the aesthetics of a tooth and protect its surface from possible damages [87]. A composite veneer can be directly placed in the mouth or fabricated in a dental laboratory, and then bonded to the visible tooth. Orthodontic composites are resins used for orthodontic dental treatments, for instance, in cementing brackets, banding or bonding, etc. [88]. Orthodontic composites are generally light-curing and release fluoride. It is preferable that patients with high aesthetic demands use composite brackets for orthodontic treatment [88].

4 Biopolymers For Electronic Applications

4.1 Organic Thin-Film Transistors (OTFTs)

Organic thin-film transistors are distinct categories of field effect transistors which use organic composites as a replacement for the conventional non-organic semiconductor materials. The main components of the physical structure of OTFTs are substrate layers, drain, gate, source, and channel. Transistor types are either the p-type or n-type semiconductor [10, 21, 78]. The main purpose of organic light emitting diodes and flexible displays is to convert electrical signals into light. Since their invention back in the 1970s, organic thin-film transistors (OTFTs) have received much research attention as part of the organic electronics field [89–91]. OTFTs are different types of field effect transistors that they employ organic composites. Commonly, the physical structure of a thin-film transistor (TFT) is mostly similar to the structure of the Field Effect Transistor (FET) they share drains, sources, gates, channels and substrate layers in structures [92]. Transistor's substrate is either the p-type semiconductor which is for electrons to be the current carriers or the n-type semiconductor which is for the holes as current carriers. The source and drain are composed of thin layers of (heavily doped) n-type or p-type semiconductors that are in contrast to the doping of the substrate. Figure 5 demonstrates a typical structure of OTFT-based flexible display.

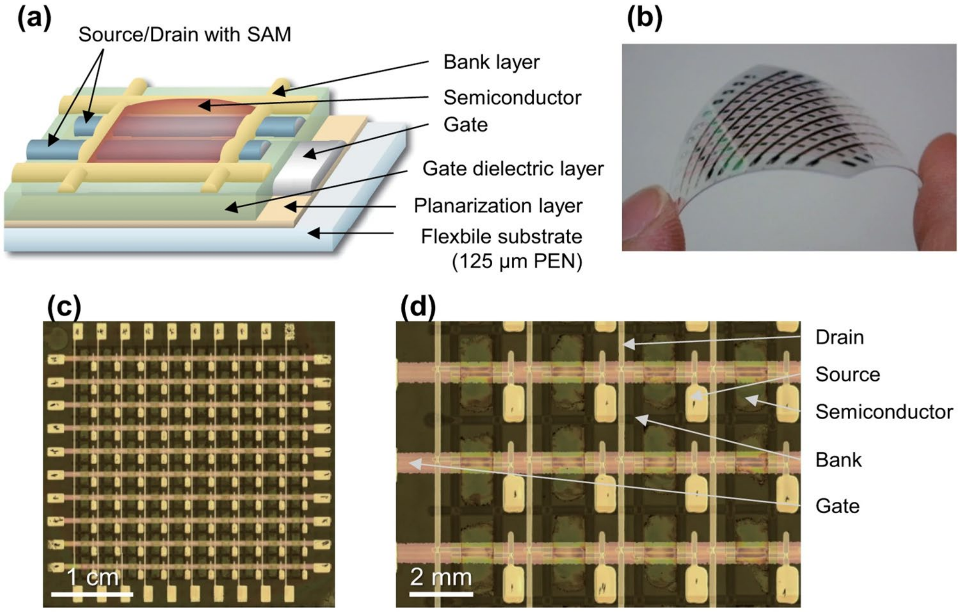


Fig. 5 Processed organic thin-film transistors-based flexible substrates, (**a**) Schematic TFTs cross-section. (**b**) TFT array on a flexible PEN substrate. (**c**) and (**d**) Microscopic optical view of TFT arrays [93]

The area between the drain and the source is insulated by a thin layer of dielectric insulation material. When an electric field occurs at the gate terminal, this will control the switching functionality of the transistor. Based on the current charge carrier of a transistor, to allow or stop electric current from flowing between the drain and source terminals, a suitable electric potential must be applied on the gate terminal relative to the source terminal. Such a flow may occur between the drain and source terminals. Let us assume that the transistor's substrate is a p-type semiconductor. To attract the free electrons from the substrate, a positive potential must be considered through the gate terminal which then forms an enhanced n-type channel underneath the gate area. This will organize the flow of the current by allowing it to flow from the drain to the substrate the moment an electric potential occurs between the source terminal and the drain. Figure 6 provides an example of a multi-layer OTFT. It is usually constructed using PDIF-CN2. It is an organic semiconductor that forms the targeted channel which travels between two 30 nm thick gold drain and source electrodes. The gate electrode is mostly composed of a 50 nm thick aluminum layer. The layers are installed on a flexible Polyethylene-Naphthalate (PEN) substrate of 100 µm thickness [78]. Figure 6 provides a diagram of a three-dimensional structure of the reported OTFT, an image of the manufactured PEN flexible wafer and an i-v characteristic curve. The i-v curve exhibits good field effect characteristics with a possible applied drain to source potential differences of up to 30 V [94]. However, the gate to source potential difference is in the range of ± 20 V and the recorded current levels are in the order of 1 µA.

4.2 Organic Light Emitting Diodes and Flexible Displays

Direct displays and Organic Light Emitting Diodes (OLEDs) are employed in material applications that convert electric signals into light using organic electronics. Biased pn-junction are used to manufacture conventional inorganic LEDs. They are composed of direct bandgap materials, such as Gallium Arsenide (GaAs). Technically, the emitted light results from a combined process within electron–hole pairs in the semiconductor material. However, when a pn-junction undergoes further biased conditions, a minority-carrier diffusion current will take place. This is due to the diffusion phenomena in the minority carriers which usually occurs at both sides of the depletion region towards the p and n areas [95]. When the carriers cross the region of depletion, a recombination with other carriers takes place. Such recombination will prompt the light emission phenomenon within the direct bandgap materials. The emitted light intensity is directly proportional to the current flowing across the diode which is in charge of the electron–hole recombination number.

4.3 Other Electronic Applications of Biopolymers

Effective electromagnetic shielding is becoming an urgent need. The electronics and communication industries have been expanding to require the operation of multiple systems within a limited area without having their features or execution affect each other. Preassigned standards of effective shielding must be met when determining the Electromagnetic Compatibility (EMC) of an electronic device or system [96]. The main requirements for materials to be considered as effective in this field include robust, eco-friendly, cost-efficient, high performance, and high shielding efficiency within wide frequency bandwidths. Reflection shielding greatly rely on metal utilizations. Optoelectronics is a wide area for biopolymers to be utilized in. It consists of photodiodes, organic semiconductor, phototransistors, and photovoltaic solar cells that found grate attention. In optoelectronic systems or devices, optics and electronics are applied for transforming electronic signals into light; and conversely. They can enable both storing and transmissions that have made them implemented in various industries including

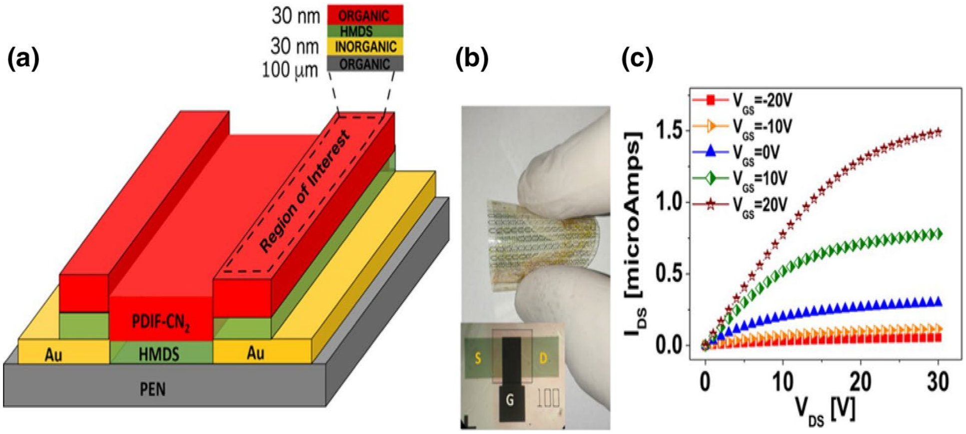


Fig. 6 (**A**) A three-dimensional structure of OTFT; (**B**) An image of flexible PEN wafer; (**C**) The i-v characteristics of the OTFT investigated by [94]

sensing, communications, detection, and medicine. Figure 7 illustrates the applications of bio-materials in electronics.

Another significant field for the use of biopolymers is energy harvesting [13, 78]. Energy harvesting generally employs the mechanical stress (piezoelectric principle) as well as temperature variations (thermoelectric principles) to capture, store, and use energy [12, 91]. Since biopolymers are flexible, they have been employed as energy harvesting materials. These bio-composites can successfully transform the applied mechanical stress from any direction into free electric charges. Some of the piezoelectric materials used are liquid crystal polymers, polyamides, and Parylene C. As for thermoelectric materials, they include Polyaniline (PANI), Polypyrrole (PPY), as well as Polythiophene (PTh) and its derivatives [98, 99]. In the electronic and communication industries, material selection depends on key properties such as bandwidth, cost, and shielding efficiency. In energy harvesting, biopolymers must exhibit additional features such as mechanical strength and temperature variations.

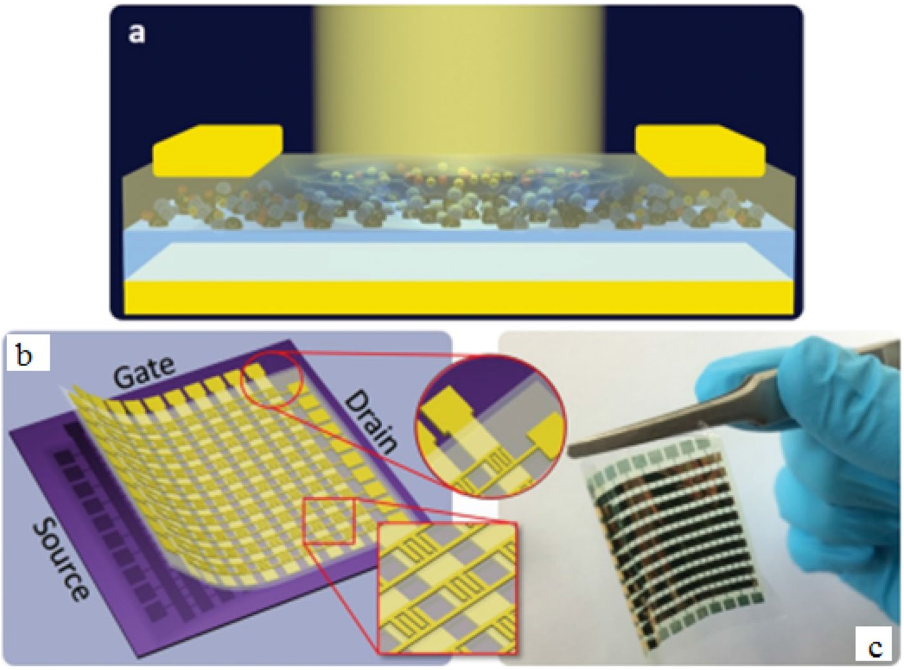
5 Biopolymers for Sustainable Food and Pharmaceutical Packaging

Certain biopolymers are directly derived from animals or plant biomass in the form of protein and polysaccharides. The former is of paramount importance to every cell, while the latter is usually found throughout the growth cycles of all organisms. Both are used to produce biodegradable materials [57, 100]. In the food and pharmaceutical packaging sectors, biodegradable polymers can be classified into three different components: proteins, lipids, and polysaccharides. In some cases, a combination of some or all three elements can be considered to produce a specific type of packaging as seen in Fig. 8.

They are suitable and competent extractions with a high potential of substituting currently used synthetic and environmentally harmful plastics [101, 102]. Additionally, food and pharmaceutical packaging composed of biopolymers can

Fig. 8 Different products made of bio-based materials (**a**) Pharmaceutical cylindrical bottle packaging, (**b**) Pharmaceutical closed packaging, (**c**) Food packaging, spoons and cups

Fig. 7 Examples of bio-materials applications in electronics, (**a**) A 3D structure demonstration of organic phototransistor's top-contact, [97], (**b**) A schematic image of the resulting pattern, (**c**) The organic transistor array [97]



protect food and drug items. They can successfully increase the duration of food preservation by preventing decay, thereby increasing the shelf life of products [103]. Promising energetic cellulosic based biopolymers like 1H-tetrazol-1-yl Acetate Functionalized Cellulosic Biopolymers (TNC and TCMC) can be utilized for biomedical applications, including, pharmaceutical applications and drug delivery, medical implants and vascular grafts. 1H-tetrazol-1-yl acetate functionalized cellulosic biopolymers are illustrated in Fig. 9.

Unmodified or monolayered biopolymers are highly sensitive to water and therefore considered as unsuitable for dry food packaging. However, biopolymers such as (PLA), Polyhydroxyalkanoates (PHAs), and their derivatives exhibit the lowest level of water–vapor permeability compared to expensive agro-based polymers such as starch, wheat gluten, and their derivatives. Thus, to produce bi-layers or composite films with low water sensitivity, a combination of both biopolymers and low-cost agro polymers (such as fibers) has been suggested [104]. Biopolymers are commonly used in the manufacturing of packaging materials for dry food goods with midterm and/or long-term shelf life such as bakery products, flour, pastry products, coffee, and grains. Table 2 demonstrates the commercial packaging applications of biopolymers. Some of these packaging are biopolymer-based PLA, paper, and cellulose-based fiber materials [24, 105, 106]. However, further efforts in the development of biodegradable packaging are highly encouraged to determine more reliable methods of protecting dry or oxidation-sensitive products from oxygen transfer or leakage.

6 Conclusions

Remarkable attainments have been achieved in the implementation of bio-composite materials, especially in the medical and electronic industries. Such expansion allows for extensive research efforts to further investigate the unlimited applications and utilizations of bio-based composites.

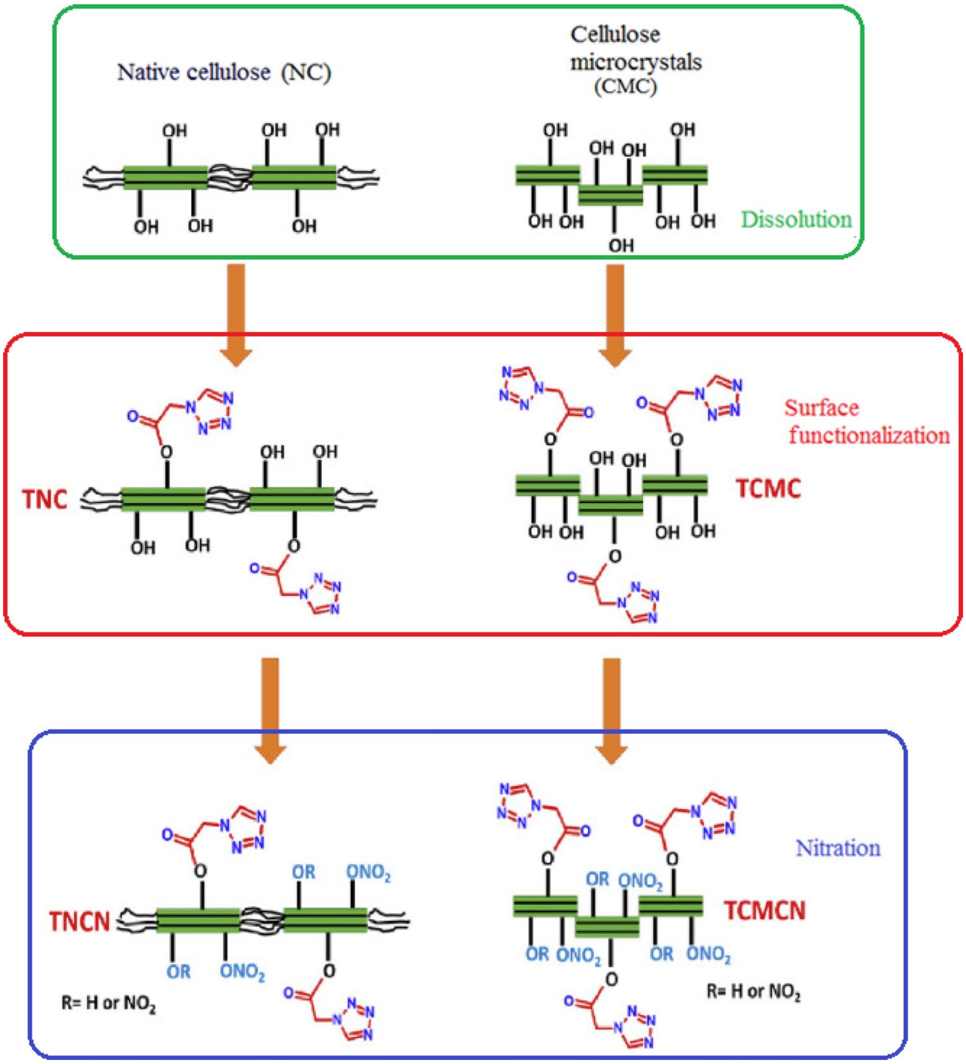


Fig. 9 Functionalized cellulosic biopolymers

Table 2 Commercial packaging applications of biopolymers

Materials	Applications	Food Examples
PLA	Transparent thermoformed trays and films	Fruits and vegetables
	PLA-based foam cups and Bags	Teabags, hot drinks from vending machines and Bread bags
	Bottles and cups	Dairy products
	Trays	Ice cream
PHA	Trays and films	Frozen and fresh foods
Starch	Semi-transparent film	Fruits and vegetables
	Barrier films for food covering	Fish, meat, cheese
	Plastic containers	Confectionaries
Cellulose	Cellophane	Fruits and vegetables (tomatoes, bell peppers, etc.)
	Barrier films and covers	Meat, fish, cheese
	Packaging films	Bread, butter, coffee beans, etc

Challenges in compatibility have also been addressed. The properties and factors which require dynamic configuration and re-characterization to meet the requirements of intended applications include high strength, hardness, fracture toughness, adhesion, solubility, polarization, plasticization, hydrogen bonding, thermal features, and dielectric properties. As promising medical interventions, biomaterials have been reported in ophthalmology, orthopedics, bone regeneration methods, bone scaffolding, and dentistry. Flowable composites and condensable composites have tremendous clinical uses. Electronically and electrically, bio-composites and biopolymers have been utilized in organic thin-film transistors, electrical applications, electromagnetic shielding, energy harvesting, and thermoelectric principles. Bio-admixtures have also been introduced as excellent examples in sustainable packaging bio-products.

7 Perspective of Further Directions

Biomaterials and biopolymers as bio-inspired and bionic materials are guided by the study of biological structure, function and principle to enhance more functional product invention and creation. Thus, it is necessary to provide a variety of strategies, such as modification of natural materials for the preparation of new functional ones for various industrial applications including drug delivery, medicine, electronic, as well as food and pharmaceutical packaging. Structure, interface and chemical composition are among the major factors that can determine the desired mechanical and electrical performance of biomaterials. Hence, proper selection schemes for the bio-inspired materials and their constituents may dramatically affect their final desired performance. Moreover, the improvement of biomaterials to produce more functional green products is closely related to the progress of advanced manufacturing technologies. Therefore, proper manufacturing for the biomaterials have to be comprehensively considered such as the bio-additive manufacturing. This technology may offer effective controls for the manufacturing process of biomaterials at multiple scales for the near future industries. Consequently, the existing challenges and future development directions of the bio-inspired materials and their applications may be advanced via proper evaluations, selections, and manufacturing strategies as well as appropriate implementations in engineering to build more realistic models to advance such biomimetic materials for more sustainable design possibilities.

Funding No funding was received to perform this work.

Data availability This work has no associated data.

Declarations

Conflict of interests The authors declare that they have no competing interests.

References

1. AlMaadeed, M. A., Kahraman, R., Noorunnisa Khanam, P., & Madi, N. (2012). Date palm wood flour/glass fibre reinforced hybrid composites of recycled polypropylene: Mechanical and thermal properties. *Materials & Design, 42*, 289–294.
2. AL-Oqla, F. M., & Sapuan, S. (2015). Polymer selection approach for commonly and uncommonly used natural fibers under uncertainty environments. *JOM Journal of the Minerals Metals and Materials Society, 67*(10), 2450–2463.
3. Peng, X., Zhang, B., Wang, Z., Su, W., Niu, S., Han, Z., & Ren, L. (2022). Bioinspired strategies for excellent mechanical properties of composites. *Journal of Bionic Engineering, 2*, 1–26.
4. Habibi, Y., El-Zawawy, W. K., Ibrahim, M. M., & Dufresne, A. (2008). Processing and characterization of reinforced polyethylene composites made with lignocellulosic fibers from Egyptian

agro-industrial residues. *Composites Science and Technology, 68*(7), 1877–1885.

5. Abral, H., Kadriadi, D., Rodianus, A., Mastariyanto, P., Arief, S., Sapuan, S. M., & Ishak, M. R. (2014). Mechanical properties of water hyacinth fibers–polyester composites before and after immersion in water. *Materials & Design, 58*, 125–129.
6. AL-Oqla, F. M., & Salit, M. S. (2017). *Materials Selection for Natural Fiber Composites* (Vol. 1). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100958-1.09993-X
7. Ahuja, T., Mir, I. A., & Kumar, D. (2007). Biomolecular immobilization on conducting polymers for biosensing applications. *Biomaterials, 28*(5), 791–805.
8. Nour, S., Baheiraei, N., Imani, R., Rabiee, N., Khodaei, M., Alizadeh, A., & Moazzeni, S. M. (2019). Bioactive materials: A comprehensive review on interactions with biological microenvironment based on the immune response. *Journal of Bionic Engineering, 16*(4), 563–581.
9. Ilyas, R., Sapuan, S., Norrrahim, M. N. F., Yasim-Anuar, T. A. T., Kadier, A., Kalil, M. S., & Abral, H. (2020). Nanocellulose/starch biopolymer nanocomposites: Processing, manufacturing, and applications. *Advanced Processing, Properties, and Applications of Starch and Other Bio-Based Polymers* (pp. 65–88). Elsevier.
10. AL-Oqla, F. M. (2020). Biocomposites in advanced biomedical and electronic systems applications. *Composites in Biomedical Applications* (pp. 49–70). CRC Press.
11. Alwani, M. S., Khalil, H. A., Sulaiman, O., Islam, M. N., & Dungani, R. (2013). An approach to using agricultural waste fibres in biocomposites application: Thermogravimetric analysis and activation energy study. *BioResources, 9*(1), 218–230.
12. AL-Oqla, F. M., & Omar, A. A. (2012). A decision-making model for selecting the GSM mobile phone antenna in the design phase to increase over all performance. *Progress In Electromagnetics Research C, 25*, 249–269. https://doi.org/10.2528/PIERC11102702
13. AL-Oqla, F. M., Omar, A. A., & Fares, O. (2018). Evaluating sustainable energy harvesting systems for human implantable sensors. *International Journal of Electronics, 105*(3), 504–517.
14. Averous, L. (2012). Synthesis, properties, environmental and biomedical applications of polylactic acid. *Handbook of Biopolymers and Biodegradable Plastics: Properties, Processing and Applications*, 171–188.
15. Cheung, H. Y., Ho, M. P., Lau, K. T., Cardona, F., & Hui, D. I. (2009). Natural fibre-reinforced composites for bioengineering and environmental engineering applications. *Composites Part B: Engineering, 40*(7), 655–663.
16. Das, P. P., Chaudhary, V., & Mishra, S. (2021). Emerging trends in green polymer based composite materials: properties, fabrication and applications. *Graphene Based Biopolymer Nanocomposites* (pp. 1–24). Springer.
17. AL-Oqla, F. M. (2020). Evaluation and comparison of date palm fibers with other common natural fibers. *Date Palm Fiber Composites* (pp. 267–286). Springer.
18. AL-Oqla, F. M., & Hayajneh, M. T. (2007). *A design decision-making support model for selecting suitable product color to increase probability* Design Challenge Conference: Managing Creativity, Innovation, and Entrepreneurship, Amman, Jordan.
19. AL-Oqla, F. M., Hayajneh, M. T., & Fares, O. (2019). Investigating the mechanical thermal and polymer interfacial characteristics of Jordanian lignocellulosic fibers to demonstrate their capabilities for sustainable green materials. *Journal of Cleaner Production, 241*, 118256.
20. AL-Oqla, F. M., & Omari, M. A. (2017). Sustainable Biocomposites: Challenges,Potential and Barriers for Development. In M. Jawaid, Sapuan, Salit Mohd, Alothman, Othman Y (Ed.), *Green biocomposites: manufacturing and properties* (pp. 13–29). Springer International Publishing (Verlag). https://doi.org/10.1007/978-3-319-46610-2
21. Fares, O., AL-Oqla, F. M., & Hayajneh, M. T. (2019). Dielectric relaxation of Mediterranean Lignocellulosic Fibers for Sustainable Functional Biomaterials. *Materials Chemistry and Physics*.
22. AL-Oqla, F. M., & Rababah, M. (2017). Challenges in design of nanocellulose and its composites for different applications. In *Cellulose-Reinforced Nanofibre Composites* (pp. 113–127). Elsevier.
23. AL-Oqla, F. M., & Sapuan, S. (2018). Investigating the inherent characteristic /performance deterioration interactions of natural fibers in bio-composites for better utilization of resources. *Journal of Polymers and the Environment, 26*(3), 1290–1296.
24. AL-Oqla, F. M., & Sapuan, S. (2020). *Advanced processing, properties, and applications of starch and other bio-based polymers*. In. Cambridge, USA: Elsevier.
25. McIlhagger, A., Archer, E., & McIlhagger, R. (2020). Manufacturing processes for composite materials and components for aerospace applications. In *Polymer composites in the aerospace industry* (pp. 59–81). Elsevier.
26. AL-Oqla, F. M. (2021). Performance trends and deteriorations of lignocellulosic grape fiber/polyethylene biocomposites under harsh environment for enhanced sustainable bio-materials. *Cellulose, 28*(4), 2203–2213.
27. Sapuan, S., Haniffah, W., & AL-Oqla, F. M. (2016). effects of reinforcing elements on the performance of laser transmission welding process in polymer composites: A systematic review. *International Journal of Performability Engineering, 12*(6), 553.
28. AL-Oqla, F. M., & Hayajneh, M. T. (2020). A hierarchy weighting preferences model to optimise green composite characteristics for better sustainable bio-products. *International Journal of Sustainable Engineering, 2*, 1–6.
29. San Ha, N., & Lu, G. (2020). A review of recent research on bio-inspired structures and materials for energy absorption applications. *Composites Part B: Engineering, 181*, 107496.
30. Alaaeddin, M., Sapuan, S., Zuhri, M., Zainudin, E., & AL-Oqla F. M. (2019). Development of photovoltaic module with fabricated and evaluated novel backsheet-based biocomposite materials. *Materials, 12*(18), 3007.
31. AL-Oqla, F. M. (2017). Investigating the mechanical performance deterioration of mediterranean cellulosic cypress and pine/polyethylene composites. *Cellulose, 24*(6), 2523–2530.
32. AL-Oqla, F. M. (2020). Flexural characteristics and impact rupture stress investigations of sustainable green olive leaves bio-composite materials. *Journal of Polymers and the Environment, 2*, 1–8.
33. AL-Oqla, F. M., Almagableh, A., & Omari, M. A. (2017). Design and fabrication of green biocomposites. *Green Biocomposites* (pp. 45–67). Berlin: Springer.
34. AL-Oqla, F. M., & El-Shekeil, Y. (2019). Investigating and predicting the performance deteriorations and trends of polyurethane bio-composites for more realistic sustainable design possibilities. *Journal of Cleaner Production, 222*, 865–870.
35. Mahmood, K., Kamilah, H., Shang, P. L., Sulaiman, S., & Ariffin, F. (2017). A review: Interaction of starch/non-starch hydrocolloid blending and the recent food applications. *Food Bioscience, 19*, 110–120.
36. Syafiq, R., Sapuan, S., Zuhri, M., Ilyas, R., Nazrin, A., Sherwani, S., & Khalina, A. (2020). Antimicrobial activities of starch-based biopolymers and biocomposites incorporated with plant essential oils: A review. *Polymers, 12*(10), 2403.
37. Jumaidin, R., Zainel, S. N. M., & Sapuan, S. (2020). Processing of thermoplastic starch. *Advanced Processing, Properties, and Applications of Starch and Other Bio-based Polymers* (pp. 11–19). Elsevier.

38. AL-Oqla, F. M., Sapuan, S., & Fares, O. (2018). Electrical–based applications of natural fiber vinyl polymer composites. *Natural Fibre Reinforced Vinyl Ester and Vinyl Polymer Composites* (pp. 349–367). Elsevier.
39. Ates, B., Koytepe, S., Ulu, A., Gurses, C., & Thakur, V. K. (2020). Chemistry, structures, and advanced applications of nanocomposites from biorenewable resources. *Chemical Reviews., 2*, 2.
40. Bayer, I. S., Guzman-Puyol, S., Heredia-Guerrero, J. A., Ceseracciu, L., Pignatelli, F., Ruffilli, R., & Athanassiou, A. (2014). Direct transformation of edible vegetable waste into bioplastics. *Macromolecules, 47*(15), 5135–5143.
41. Bhatti, H. N., Mahmood, Z., Kausar, A., Yakout, S. M., Shair, O. H., & Iqbal, M. (2020). Biocomposites of polypyrrole, polyaniline and sodium alginate with cellulosic biomass: Adsorption-desorption, kinetics and thermodynamic studies for the removal of 2, 4-dichlorophenol. *International Journal of Biological Macromolecules., 2*, 2.
42. Koller, M., Maršálek, L., de Sousa Dias, M. M., & Braunegg, G. (2017). Producing microbial polyhydroxyalkanoate (PHA) biopolyesters in a sustainable manner. *New Biotechnology, 37*, 24–38.
43. Mazerolles, T., Heuzey, M.-C., Soliman, M., Martens, H., Kleppinger, R., & Huneault, M. A. (2020). Development of multilayer barrier films of thermoplastic starch and low-density polyethylene. *Journal of Polymer Research, 27*(2), 1–15.
44. Jiang, T., Duan, Q., Zhu, J., Liu, H., & Yu, L. (2020). Starch-based biodegradable materials: Challenges and opportunities. *Advanced Industrial and Engineering Polymer Research, 3*(1), 8–18.
45. Thakur, R., Pristijono, P., Scarlett, C. J., Bowyer, M., Singh, S., & Vuong, Q. V. (2019). Starch-based films: Major factors affecting their properties. *International Journal of Biological Macromolecules, 132*, 1079–1089.
46. Zhu, F. (2019). Starch based Pickering emulsions: Fabrication, properties, and applications. *Trends in Food Science & Technology, 85*, 129–137.
47. Abral, H., Basri, A., Muhammad, F., Fernando, Y., Hafizulhaq, F., Mahardika, M., & Stephane, I. (2019). A simple method for improving the properties of the sago starch films prepared by using ultrasonication treatment. *Food Hydrocolloids, 93*, 276–283.
48. Ilyas, R., Sapuan, S., Atiqah, A., Ibrahim, R., Abral, H., Ishak, M., & Ansari, M. (2020). Sugar palm (Arenga pinnata [Wurmb.] Merr) starch films containing sugar palm nanofibrillated cellulose as reinforcement: Water barrier properties. *Polymer Composites, 41*(2), 459–467.
49. Omran, A. A. B., Mohammed, A. A., Sapuan, S., Ilyas, R., Asyraf, M., Rahimian Koloor, S. S., & Petrů, M. (2021). Micro-and nanocellulose in polymer composite materials: A review. *Polymers, 13*(2), 231.
50. Yamada, M., Morimitsu, S., Hosono, E., & Yamada, T. (2020). Preparation of bioplastic using soy protein. *International Journal of Biological Macromolecules, 149*, 1077–1083.
51. Xu, C., Xu, Y., Chen, M., Zhang, Y., Li, J., Gao, Q., & Shi, S. Q. (2020). Soy protein adhesive with bio-based epoxidized daidzein for high strength and mildew resistance. *Chemical Engineering Journal, 390*, 124622.
52. Ilyas, R., Sapuan, S., Sanyang, M. L., Ishak, M. R., & Zainudin, E. (2018). Nanocrystalline cellulose as reinforcement for polymeric matrix nanocomposites and its potential applications: A review. *Current Analytical Chemistry, 14*(3), 203–225.
53. Siakeng, R., Jawaid, M., Ariffin, H., Sapuan, S., Asim, M., & Saba, N. (2019). Natural fiber reinforced polylactic acid composites: A review. *Polymer Composites, 40*(2), 446–463.
54. Vinod, A., Sanjay, M., Suchart, S., & Jyotishkumar, P. (2020). Renewable and sustainable biobased materials: An assessment on biofibers, biofilms, biopolymers and biocomposites. *Journal of Cleaner Production, 258*, 120978.
55. Souzandeh, H., Wang, Y., Netravali, A. N., & Zhong, W.-H. (2019). Towards sustainable and multifunctional air-filters: A review on biopolymer-based filtration materials. *Polymer Reviews, 59*(4), 651–686.
56. Taskin, M. B., Ahmad, T., Wistlich, L., Meinel, L., Schmitz, M., Rossi, A., Groll, J., & r. (2021). bioactive electrospun fibers: fabrication strategies and a critical review of surface-sensitive characterization and quantification. *Chemical Reviews., 2*, 2.
57. Azeredo, H., Barud, H., Farinas, C. S., Vasconcellos, V. M., & Claro, A. M. (2019). Bacterial cellulose as a raw material for food and food packaging applications. *Frontiers in Sustainable Food Systems, 3*, 7.
58. Yadav, B., Talan, A., Tyagi, R., & Drogui, P. (2021). Concomitant production of value-added products with polyhydroxyalkanoate (PHA) synthesis: A review. *Bioresource Technology, 2*, 125419.
59. Das, O., Kim, N. K., Hedenqvist, M. S., Bhattacharyya, D., Johansson, E., Xu, Q., & Holder, S. (2020). Naturally-occurring bromophenol to develop fire retardant gluten biopolymers. *Journal of Cleaner Production, 243*, 118552.
60. Sapuan, S. M., Pua, F.-L., El-Shekeil, Y. A., & AL-Oqla, F. M. (2013). Mechanical properties of soil buried kenaf fibre reinforced thermoplastic polyurethane composites. *Materials & Design, 50*, 467–470. https://doi.org/10.1016/j.matdes.2013.03.013
61. Alaaeddin, M., Sapuan, S., Zuhri, M., Zainudin, E., & AL-Oqla, F. M. (2019). Polymer matrix materials selection for short sugar palm composites using integrated multi criteria evaluation method. *Composites Part B: Engineering, 2*, 107342.
62. Alaaeddin, M., Sapuan, S., Zuhri, M., & Zainudin, E. (2019). Physical and mechanical properties of polyvinylidene fluoride-Short sugar palm fiber nanocomposites. *Journal of Cleaner Production, 235*, 473–482.
63. AL-Oqla, F. M., S. M. Sapuan, M. R. Ishak, & A.A., N. (2015, March, 3, 2015). Selecting natural fibers for industrial applications. Postgraduate Symposium on Biocomposite Technology Serdang, Malaysia.
64. AL-Oqla, F. M., Sapuan, M. S., Ishak, M. R., & Aziz, N. A. (2014). Combined multi-criteria evaluation stage technique as an agro waste evaluation indicator for polymeric composites: Date palm fibers as a case study. *BioResources, 9*(3), 4608–4621. https://doi.org/10.15376/biores.9.3.4608-4621
65. AL-Oqla, F. M., Sapuan, M. S., Ishak, M. R., & Nuraini, A. A. (2015). Decision making model for optimal reinforcement condition of natural fiber composites. *Fibers and Polymers, 16*(1), 153–163.
66. AL-Oqla, F. M., Sapuan, S., & Jawaid, M. (2016). Integrated mechanical-economic–environmental quality of performance for natural fibers for polymeric-based composite materials. *Journal of Natural Fibers, 13*(6), 651–659.
67. Jamshidian, M., Tehrany, E. A., Imran, M., Jacquot, M., & Desobry, S. (2010). Poly-lactic acid: Production, applications, nanocomposites, and release studies. *Comprehensive Reviews in Food Science and Food Safety, 9*(5), 552–571.
68. Lai, G., Zhao, L., Wang, J., & Kunzelmann, K.-H. (2018). Surface properties and color stability of dental flowable composites influenced by simulated toothbrushing. *Dental Materials Journal, 2*, 2017–2233.
69. Peterson, J., Rizk, M., Hoch, M., & Wiegand, A. (2018). Bonding performance of self-adhesive flowable composites to enamel, dentin and a nano-hybrid composite. *Odontology, 106*(2), 171–180.

70. Butcher, A. L., Offeddu, G. S., & Oyen, M. L. (2014). Nanofibrous hydrogel composites as mechanically robust tissue engineering scaffolds. *Trends in Biotechnology, 32*(11), 564–570.
71. Guimard, N. K., Gomez, N., & Schmidt, C. E. (2007). Conducting polymers in biomedical engineering. *Progress in Polymer Science, 32*(8), 876–921.
72. Al-Ghraibah, A. M., Al-Qudah, M., & AL-Oqla, F. M. (2020). medical implementations of biopolymers. *Advanced Processing, Properties, and Applications of Starch and Other Bio-Based Polymers* (pp. 157–171). Elsevier.
73. Shera, S. S., & Banik, R. M. (2021). development of tunable silk fibroin/xanthan biopolymeric scaffold for skin tissue engineering using l929 fibroblast cells. *Journal of Bionic Engineering, 18*(1), 103–117.
74. Jiang, Q., Reddy, N., & Yang, Y. (2010). Cytocompatible cross-linking of electrospun zein fibers for the development of water-stable tissue engineering scaffolds. *Acta Biomaterialia, 6*(10), 4042–4051.
75. Hardy, J. G., Lee, J. Y., & Schmidt, C. E. (2013). Biomimetic conducting polymer-based tissue scaffolds. *Current Opinion in Biotechnology, 24*(5), 847–854.
76. Freeman, R., Boekhoven, J., Dickerson, M. B., Naik, R. R., & Stupp, S. I. (2015). Biopolymers and supramolecular polymers as biomaterials for biomedical applications. *MRS Bulletin, 40*(12), 1089–1101.
77. Modjarrad, K., & Ebnesajjad, S. (2013). *Handbook of polymer applications in medicine and medical devices*. Elsevier.
78. Fares, O. O., & AL-Oqla, F. M. (2020). Modern electrical applications of biopolymers. *Advanced Processing, Properties, and Applications of Starch and Other Bio-Based Polymers* (pp. 173–184). Elsevier.
79. Jun, S.-K., Cha, J.-R., Knowles, J. C., Kim, H.-W., Lee, J.-H., & Lee, H.-H. (2020). Development of Bis-GMA-free biopolymer to avoid estrogenicity. *Dental Materials, 36*(1), 157–166.
80. Szczesio-Wlodarczyk, A., Domarecka, M., Kopacz, K., Sokolowski, J., & Bociong, K. (2021). An evaluation of the properties of urethane dimethacrylate-based dental resins. *Materials, 14*(11), 2727.
81. Pałka, K. (2020). Polymerization shrinkage of new dental composites modified with liquid rubber. *Engineering of Biomaterials, 23*(158 spec. iss.).
82. Loumprinis, N., Maier, E., Belli, R., Petschelt, A., Eliades, G., & Lohbauer, U. (2021). Viscosity and stickiness of dental resin composites at elevated temperatures. *Dental Materials, 37*(3), 413–422.
83. Srivastava, S. K., & Pal, B. G. (2018). Metallic biomaterials for dental implant systems. *Fundamental Biomaterials: Metals* (pp. 111–137). Elsevier.
84. Baggio, A. M. P., Guiotti, A. M., de Almeida, J. M., Ferriolli, S. C., Delamura, I. F., & Bassi, A. P. F. (2021). Agenesis treatment with osseointegrated implant and filling of the buccal bone plate with biomaterial. *Research, Society and Development, 10*(6), e40110615783–e40110615783.
85. Cekic-Nagas, I., Egilmez, F., Ergun, G., Vallittu, P. K., & Lassila, L. V. J. (2017). Load-bearing capacity of novel resin-based fixed dental prosthesis materials. *Dental Materials Journal, 2*, 2016–2367.
86. Perea-Lowery, L., & Vallittu, P. K. (2018). Framework design and pontics of fiber-reinforced composite fixed dental prostheses-an overview. *Journal of Prosthodontic Research, 62*(3), 281–286.
87. Reis, G. R., Vilela, A. L. R., Silva, F. P., Borges, M. G., de Freitas Santos-Filho, P. C., & de Sousa Menezes, M. (2017). Minimally invasive approach in esthetic dentistry: Composite resin versus ceramics veneers. *Bioscience Journal, 33*, 1.
88. Assery, M. K., Ajwa, N., Alshamrani, A., Alanazi, B. J., Durgesh, B. H., & Matinlinna, J. P. (2019). Titanium dioxide nanoparticles reinforced experimental resin composite for orthodontic bonding. *Materials Research Express, 6*(12), 125098.
89. Liu, L., Liang, H., Zhang, J., Zhang, P., Xu, Q., Lu, Q., & Zhang, C. (2018). Poly (vinyl alcohol)/Chitosan composites: Physically transient materials for sustainable and transient bioelectronics. *Journal of Cleaner Production, 195*, 786–795.
90. Sun, S.-S., & Dalton, L. R. (2008). *Introduction to Organic Electronic and Optoelectronic Materials and Devices*. CRC Press.
91. AL-Oqla, F. M., & Omar, A. A. (2015). An expert-based model for selecting the most suitable substrate material type for antenna circuits. *International Journal of Electronics, 102*(6), 1044–1055.
92. Chen, J.-X., Li, X.-X., Tao, J.-J., Cui, H.-Y., Huang, W., Ji, Z.-G., & Zhang, D. W. (2020). Fabrication of a Nb-doped β-Ga2O3 nanobelt field-effect transistor and its low-temperature behavior. *ACS Applied Materials & Interfaces, 12*(7), 8437–8445.
93. Fukuda, K., Takeda, Y., Mizukami, M., Kumaki, D., & Tokito, S. (2014). Fully solution-processed flexible organic thin film transistor arrays with high mobility and exceptional uniformity. *Scientific reports, 4*(1), 1–8.
94. Tortora, L., Urbini, M., Fabbri, A., Branchini, P., Mariucci, L., Rapisarda, M., & Di Capua, F. (2018). Three-dimensional characterization of OTFT on modified hydrophobic flexible polymeric substrate by low energy Cs+ ion sputtering. *Applied Surface Science, 448*, 628–635.
95. Fukagawa, H., Sasaki, T., Tsuzuki, T., Nakajima, Y., Takei, T., Motomura, G., & Shimizu, T. (2018). Long-lived flexible displays employing efficient and stable inverted organic light-emitting diodes. *Advanced Materials, 30*(28), 1706768.
96. Iqbal, A., Sambyal, P., & Koo, C. M. (2020). 2D MXenes for electromagnetic shielding: A review. *Advanced Functional Materials, 30*(47), 2000883.
97. Chu, Y., Wu, X., Lu, J., Liu, D., Du, J., Zhang, G., & Huang, J. (2016). Photosensitive and flexible organic field-effect transistors based on interface trapping effect and their application in 2D imaging array. *Advanced Science, 3*(8), 1500435.
98. Cui, H., Hensleigh, R., Yao, D., Maurya, D., Kumar, P., Kang, M. G., & Zheng, X. R. (2019). Three-dimensional printing of piezoelectric materials with designed anisotropy and directional response. *Nature Materials, 18*(3), 234–241.
99. Chen, J., Qiu, Q., Han, Y., & Lau, D. (2019). Piezoelectric materials for sustainable building structures: Fundamentals and applications. *Renewable and Sustainable Energy Reviews, 101*, 14–25.
100. Majeed, K., Jawaid, M., Hassan, A., Bakar, A. A., Khalil, H. A., Salema, A. A., & Inuwa, I. (2013). Potential materials for food packaging from nanoclay/natural fibres filled hybrid composites. *Materials & Design, 46*, 391–410.
101. Sanyang, M., Ilyas, R., Sapuan, S., & Jumaidin, R. (2018). Sugar palm starch-based composites for packaging applications. *Bionanocomposites for Packaging Applications* (pp. 125–147). Springer.
102. Sanyang, M., & Sapuan, S. (2015). Development of expert system for biobased polymer material selection: Food packaging application. *Journal of Food Science and Technology, 52*(10), 6445–6454.
103. Spiridon, I., Ursu, R. G., & Spiridon, I. A. C. (2015). New polylactic acid composites for packaging applications: Mechanical properties, thermal behavior, and antimicrobial activity. *International Journal of Polymer Analysis and Characterization, 20*(8), 681–692.
104. Rababah, M. M., & AL-Oqla, F. M. (2020). Biopolymer composites and sustainability. *Advanced Processing, Properties, and Applications of Starch and Other Bio-Based Polymers* (pp. 1–10). Elsevier.
105. Amara, C., El Mahdi, A., Medimagh, R., & Khwaldia, K. (2021). Nanocellulose-based composites for packaging applications.

Current Opinion in Green and Sustainable Chemistry, 31, 100512.

106. Zhou, Y., Liu, F., & Wang, H. (2017). Novel organic–inorganic composites with high thermal conductivity for electronic packaging applications: A key issue review. *Polymer Composites, 38*(4), 803–813.