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Green Sustainable Bionanocomposites Materials: Short Review

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A B S T R A C T

This article provides a comprehensive overview of the most recent developments in the study and creation of bionanocomposites, which find use in a variety of fields including tissue engineering, food packaging, cosmetics, electronic industries and biomedical applications. Renewable energy, low carbon footprints and biodegradability concerns have fuelled the emergence of biobased materials and enabled them to transition from market segment to high volume applications. Bionanocomposites can overcome the intrinsic disadvantages of some biobased plastics including their limited manufacturing window, inadequate barrier, conductivity, hydrophilicity, lower biocompatibility and relatively low deflection temperature. The first section of the paper examines the benefits and drawbacks of recent developments in the creation of biodegradable materials from resources that are renewable. The second section discusses different kinds of bionanocomposites relying on: cellulose, starch, polylactic acid and protein. Additionally, current developments in processing technological advances, product growth and applications are also presented in this review.

1. INTRODUCTION

A human hair is around 80,000 times smaller than a nanometer, which is equal to the billionth of a metre (10^{-9} m). In recent years, materials that are composite at the nanoscale were previously examined [1]. A new category of nanocomposite materials called nanostructured composites has been identified. As of right now, nanocomposites made of polymer are defined as an amalgamation of polymers and additives with a size lower than 100 nm [2,3]. The constituents of a nanocomposite material can be made up of various inorganic/inorganic, inorganic/organic, or organic/organic substances [4]. Because of the various benefits they provide, nanocomposites have currently acquired relevance. The initial one is their commercial importance in the design of new constructions and substances made of unique materials with extraordinary flexibilities. Second, since they have essentially no flaws, uses of nanoscale filler get beyond the limitations of conventional methods. Furthermore, due to their substantial particular surface region, nanocomposites are distinct from bulk polymers in that they exhibit a significant amount of intermediate structural material (interphase). Since nanocomposites made of polymers have a wide range of uses, it is difficult to estimate their properties [5]. With here, the concept of using biopolymers that in place of traditional polymers to create "bionanocomposites"—bio-based nanocomposites—was born. The subsequent two definitions apply to bionanocomposites, which extend the notion of biocomposites [6] to nanostructured matter hybrid materials. It might define nanocomposites as substances made of petroleum-based polymers like polyethylene, polypropylene, nylon, epoxies and sustainable nanoparticles (like whiskers of cellulose). However, bionanocomposites also include nanocomposites made of artificial or inorganic additives (like nanotubes made of carbon and clay) and biopolymers (like polylactic acid and polyhydroxyalkanoates). The prefix "bio" in the "biopolymers" designates that they can be broken down by biological processes. Because biopolymers are broken down by commonly existing organisms and produce organic compounds (such as carbon dioxide and water) as a result, they usually have a low environmental impact. Biopolymers that are the perfect substitutes for plastics made from petroleum since they are plentiful, sustainable and recyclable in nature [7,8].

2. BIONANOCOMPOSITES

Researchers are interested in bionanocomposites as they provide new opportunities and act as a bridge among materials engineering, biology, and nanostructures. They are currently beneficial in the domain of bioengineering as well. Biopolymers such as cellulose, lipopeptides and enzymes, aromatic polycaprolactide, and polynucleic acids are used to present bionanocomposites, whereas binders such as kaolinite, calcium phosphate, and metal oxide nanoparticles are used as fillers [9]. Bionanocomposites are also called as "biocomposites," "green composites," or "biohybrids," all of which are abbreviated as "bioplastics." They exhibit various qualities like as thermal properties, solubility, cytocompatibility and degradability, which govern the processes of preparation, capabilities and specific implementations of materials. Nanocomposites differ from composites in that they contain petroleum-based polymers as an organic phase, whereas composite materials are made up of inorganic ingredients at the nanoscale level [10]. Furthermore, one substantial variation among bionanocomposites and biocomposites is that the former may be composed of biodegradable polymers but lack the nanosized additives shown in Fig. 1. These biopolymers are accessible in hydrophilic solvents, but petroleum-derived polymers are more permeable in organic solvents. While there are some commonalities, there are also some variations, such as preparation processes, characteristics, bioactivity, and biocompatible. Surprisingly, the geometry of nanoparticles has a significant influence in the production of bionanocomposites and in determining their properties. On the basis of shape, the nanoparticulates can be divided into a number of categories, including nano rods, nanoplatelets, and nanotubes [11].

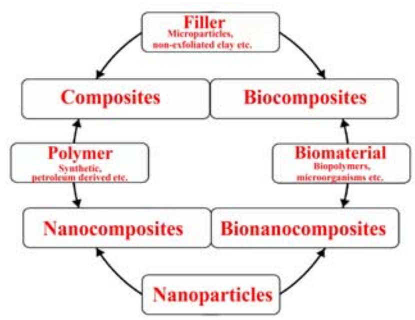

Fig. 1. The most common composite materials and their ingredients (own source).

The development of bionanocomposites has been made possible by the limits of nanocomposites. Fabricating the nanocomposite matrix is one of the biggest obstacles. There are a number of drawbacks to creating nanocomposites through pre- or post-polymerization [12]. Nanoparticles can infiltrate aquatic environments through a number of different channels, such as discharge from factories or sewage clean up, etc. Through various chemical and biological reactions occurring in the environment, they can be changed into a number of distinct forms. Higher species can directly consume these tiny particles. Additionally, both land and marine animals are capable of binding together nanoparticles [13]. A new class of materials called as bionanocomposites is the result of all these characteristics. In order to compete with materials made from petroleum and simultaneously retain an equilibrium between sustainable, economy, and science and technology, bionanocomposites with a considerable amount of bio-based element can provide a significant cost effective performance. As a result, they might be regarded as green materials.

The concept of "green" has recently been established as an emerging standard for materials, technological advances, and goods. Resources, technology, and goods that are considered "green" often have either a beneficial or detrimental effect on the environment than their conventional analogues to human wellness [14]. Biodegradation is the process of breaking down a substance in its natural state in order to ensure any changes to the material's chemical-based, related to structure, or mechanical characteristics either demonstrate to be environmentally friendly to the surroundings or seem to help it in some way [15,16]. Sustainable and recyclable materials for composites are regarded as being "green." They may be rid of properly by composting or other means. However, the use of environmentally friendly polymers in the making of the green composites is the main problem. Natural materials such as acetate of cellulose, carbohydrates and lignin are used to make polymers. While some artificial polymers (such as aromatic and aliphatic polyester-based materials, etc.) are bio polymers and biodegradable [17], they are not regenerative. As a result, these do not fully adhere to the concepts of decomposition and renewability. Numerous polymers that occur naturally and other biodegradable materials have been used to create green hybrids; several of them are covered in the subsequent parts of this section [18]. Consequently, a variety of bio polymers may prove beneficial for different uses. Their application appears challenging due to its weak structural and protective qualities. But the qualities of composites may be enhanced by adding reinforcement in the shape of nanoscale chemicals or fillers.

3. BIONANOCOMPSITES CHARACTERISTICS

The importance of sustainable polymeric materials, which are eco-friendly, cannot be overstated in the biomedical and healthcare sectors [19]. Due to the excellent surface to volume proportion and enhanced surface response of their nano-sized antimicrobial substances, composites make the perfect antibacterial systems. Relative to their macro- or micro-scale analogues, this has a stronger capacity for inactivating microbes [20]. The ability of a biomaterial to be used in medical treatments and its biological compatibility (i.e., the material ought to be capable to operate effectively in the body of a person without having any significant side effects and simultaneously be willing to produce an ideal medical result) are two of its most crucial qualities [21]. The best sustainable composites for medical purposes, including vaccines, drug delivery systems, engineering of tissues, and dressings for wounds, are bio-nanocomposites due to their superior mechanical characteristics, the ability to degrade and biological compatibility [22, 23]. They can also be used as an enhanced antibacterial film technology for packaging food that is sustainable, economical, and environmentally beneficial. Starch and cellulose derivatives, polyhydroxybutyrate (PHB) and poly - (butylene succinate) (PBS) are a few of the renowned composites made from bio used for packing equipment.

Combining bio polymers like glucose and PLA with nanofillers to create bionanocomposites may result in materials with innovative, outstanding features since nanofillers can improve the thermal processing, mechanical, and insulating properties. Numerous studies have been conducted on the effects of nanofillers on the characteristics of bionanocomposites [24]. In many places, eco-friendly materials have undoubtedly taken the place of chemicals based on petroleum. More environmentally friendly materials, such bionanocomposites, are produced by novel developments and improvements in microbiology and nanomaterials for a variety of purposes in numerous scientific fields.

4. BIONANOCOMPOSITES CLASSIFICATION

We can categorize bionanocomposites based on a variety of criteria. A few of the factors may include the origination, size, and structure of the incorporations, as well as the form of matrix employed. The following is a categorization of bionanocomposites based on particle incorporation shape.

- Perforated bionanocomposites: These bionanocomposites are made up of dimensions particles that act as reinforcements and help to mitigate a low reinforcing impact. Because of the low perspective ratio, that is the case. Furthermore, the primary goal of adopting these additions is to decrease permeability, render them combustible, and decrease the price of composite [25].
- Elongated ingredient bionanocomposites: These bionanocomposites are formed by using extended nanoparticles as reinforcement, such as silk nanofibers and nanotubes. They show the reinforcement's substantial aspect ratio and so provide improved biomechanical behaviour [26].
- Stacked polymer nanocomposites: These may also be termed as multilayer particle-reinforced bionanocomposites. Based on the dissemination rate in the medium, multiple sub-classes (nanomaterials, microcomposites, infiltrated and delaminated nanocomposite) may exist. Microparticles distributed in a polymer - based matrix serve as microcomposites. Moreover, polymer molecules agglomerated across layers of stratified nanoparticles create interstitial nanostructures, whereas specific layer partitioning leads in highly porous nanocomposites [27].

5. BIONANOCOMPOSITES APPLICATIONS

Bionanocomposites (green) composites has been investigated for use in vehicle goods or parts. Lignin nanofibers are employed to create long-lasting load - carrying materials, auto components, and car structural components. Moreover, they were employed as suction cleaner rotors, phone accessories, and power equipment housings [28]. PLA-based matrix composites have been suggested to be employed for bioengineering implants due to their high biological properties. Other products utilising bionanocomposites involve: cellulose fibers paper to generate ID tags with brilliant computational power and RF potential, while the same may be employed to create cheap ID tags for uses to identify illegal goods or monitor commodities remotely, among other comparable applications. Cellulosic nanofibers have additionally been employed commercially as food and medicinal package material, such as paperboards for lactose and flavoured goods [29]. As a result, we can conclude that "ecofriendly" nanocomposites have significance in crucial sectors like aviation defence. Polysaccharides like cellulose, glucose, alginate, and several have newly captured the research community's interest owing to their renewability and biodegradability, which enables for varied formulations to be utilized for different applications. The preceding is a comprehensive discussion of some bionanocomposites.

5.1 Bionanocomposites relying on cellulose

The creation of cellulose nanoparticles as the most self-sustaining materials that meet all of the standards for being an "ecofriendly" material is one of the outstanding accomplishments of the twenty-first century [30]. Cellulose is among the most prevalent biopolymers on the earth. It is one of the sustainable biopolymers that offer a substitute to exhaustible, crude oil-based goods, helping to lessen reliance on the latter. Cellulose is a D-glucose-based linear polysaccharide. It is made up of linear lactose connections, with C-1 of each glucose unit linked to C-4 of the following molecule of glucose, as can be seen in Fig. 2. Some remarkable aspects of this naturally high polymer include its extremely crystalline structure and infusibility. To produce cellulose better processable, it is transformed into compounds such as cellulose ketones and cellulose aromatics due to its high infusibility. Besides from possessing a sustainable and inexpensive substance, cellulose composites have several other features, such as higher strength and fracture toughness [31].

Aziz-Lalabadi and Jafari produced unique bionanocomposite materials with superior mechanical, thermal, photonic, and protective characteristics for applications such as packaging [32]. A carboxylated lignocellulosic polymeric matrix containing fibre nanostructures as reinforcement was used to create the films. Sugiarto et al. revealed some promising findings on rejuvenated biocomposite micro composite coatings that shown anti-microbial activity towards Staphylococcus infections [33]. These findings cleared the path for nanocomposite to be used in practical packaging materials. Furthermore, nanofibers are inexpensive and widely accessible, and it has numerous advantages, notably antibacterial and chemical characteristics. As a result, nanocellulose-based nanostructures are highly suited for water filtration.

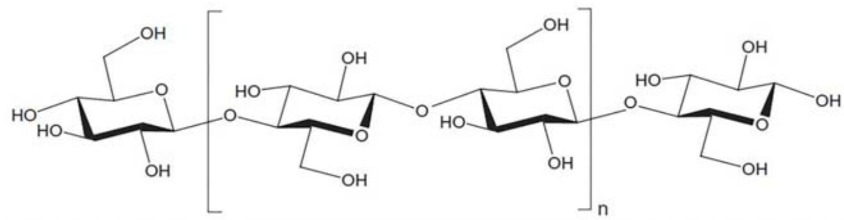

Fig. 2. Cellobiose repetitive unit is visible in the basic molecular framework of cellulose.

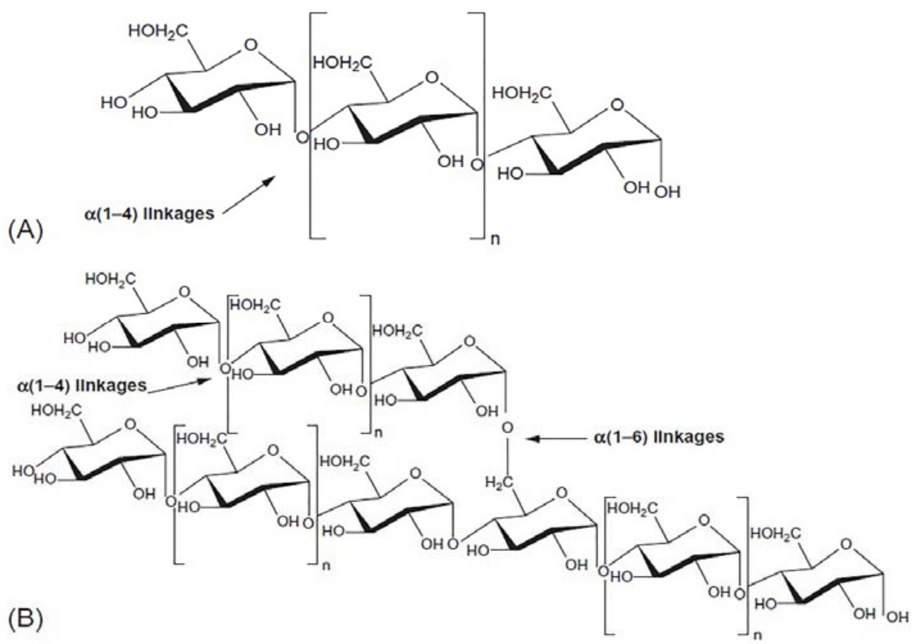

Fig. 3. (A) Amylase and (B) amylopectin chemical structures.

5.2 Bionanocomposites relying on starch

Starch is the key provider of energy in plants and is stored for long periods of time in stems, plants, spores, and branches. A starch flake is a glycoprotein made up of two polymeric materials: amylase (around 10%-30% of the particle) and amylopectin (the residual 70%-90% of the globules) [34]. Amylose is made up of a lengthy sequential manner of (1-4)-linked D-glucose units with a level of polymerization varying from 300 to 10,000 [35]. Amylopectin is an extremely high polymeric having an amylase framework that is cross-linked via (1-6) linkages [36]. Fig. 3 depicts the varied architectures of amylose and amylopectin. Starch has outstanding qualities such as low toxicity, biodegradability, good biocompatibility, and favourable mechanical characteristics, which are relevant in the field of biomedical applications. Drug delivery methods, bone regeneration treatments, biomaterial, and hydrogels are some of the applications. Carbon nanotubes (CNTs) have previously been investigated for medicinal uses, including their use as reinforcing that can also drive bone development. Hasnain and Nayak investigated the use of starch-based nanostructured materials and multi-walled nanotubes as bone-regenerating therapeutics or bone grafts [37]. Similarly, nanomaterials were used to create antimicrobial starch-based coatings for biomedical purposes.

Pop et al. created silver nanorods on a waxed matrix phase, which demonstrated outstanding bactericidal activity against Gram-negative and Gram-positive microorganisms [38]. Moreover, starch-clay bionanocomposites can also be utilized for food packaging applications.

5.3 Bionanocomposites relying on polylactic acid

Poly-lactic acid (PLA) is synthesised chemically or by fermenting from lactate acid, a sole unit of hydroperoxides formic acid. On an industrial level, lactic acid is produced through fermentation instead of chemical processing as shown in Fig. 4. This really is due to the fact that the synthesised routes have numerous drawbacks, such as the essence that the response is not stereoselective (i.e., the preferable creation of L-lactic acid stereoisomers), limited ability due to reliance on a by-product of some other method, and high analysis costs [39]. PLA is a popular polymeric for biological applications because it can be manufactured under controlled circumstances. It also has impressive features such as biodegradability, elastic strength, and strength properties. PLA also exhibits good osteogenesis and cytocompatibility in vivo. Although having outstanding mechanical and physical qualities (such as biocompatibility and ability to decompose), PLA fails a few of the basic requirements of biomaterials. Retaining structural strength during tissue formation is one of these features. PLA should stimulate and encourage tissue regeneration while also maintaining the quantity of fresh tissue formation while maintaining the rate of breakdown in biomedical applications [40]. This has attracted scientists' interest in learning further about PLA-based polymeric multifunctional biomaterials.

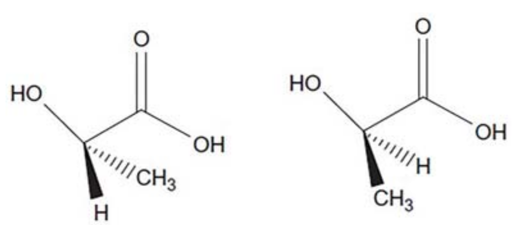

Fig. 4. Lactic acid Stereoisomers.

Furthermore, homogenous dispersal of metallic nanoparticles can change the texture of the PLA material surface, which improves living cell adherence on the bionanocomposite surface. Metallic nanoparticles including as platinum, gold, and silver are commonly used in the manufacture of PLA biocomposites. The addition of metal nanocomposites increases the heat conductivity of the bionanocomposite, resulting in a faster breakdown of the PLA matrices [41].

5.4 Bionanocomposites relying on protein

Proteins such as wheat flour, soybean, maize zein, and others may form an excellent film, which makes them a perfect substance for biodegradable materials. As a result, they are ideal for the production of bionanocomposites [42]. Several hydrogels have been created in the past employing protein-based silver nano - composites that can be used for a wide range of biomedical uses. Jao et al. used wheat protein-based hydrogel nanomaterials for antibacterial purposes [43]. Collagen was also shown to be included with curcumin films to treat cutaneous lesions. Furthermore, coupling proteins with polysaccharides including such alginate, glucose, and gelatin can increase their functional characteristics. Until the 1950s, when petroleum-based polymers still were unknown, these proteins were employed. Collagen I is the extensively explored collagen and can be found in the bone and skin tissues. Collagen I has good cell adherent, biomechanical, and osteogenic qualities, making it useful for tissue engineering applications. Collagen-containing bionanocomposites are typically combined with nanoparticle hydroxyapatite and are beneficial in the development of prostheses and biomimic bone cells [44]. Sol-gel cryogenic drying was used to develop novel collagen/ZnTiO3 nanocomposites, resulting in a reasonably uniform dispersion of ZnTiO3 nanoparticles in an accessible, linked, uniform pore structure. Collagen/ZnTiO3 nanocomposites are novel anti-infective nanomaterials with antimicrobial and broad-spectrum antimicrobial properties and lower toxicity to biological systems [45].

Soy protein has attracted the research society's attention due to its thermoplastic qualities. Despite its considerable promise as a bioplastic, its degradation rate has not been properly explored due to its poor moist reactivity and high stiffness [46]. As contrasted to equivalents lacking fillers, soy protein nanocomposites demonstrated better mechanical strength, percentage of elongation, and decreased water vapour penetration. Zein (corn protein), a moderately hydrophobic protein present in corn kernels, is recognized to quickly create films. Zein is utilised as a capping material in the food sector and has showed ability as a recyclable polymer. Despite the fact that zein polymers are less moisture reactive than other natural polymers, they nonetheless have weak tensile strength and significant hydrophilicity when contrasted to commercial polymers [47].

Bionanocomposites have enormous prospects as future environmentally friendly materials made up of biopolymers and related composites that proven to be a more cost-effective alternative to petro-based polymers. Formerly, great attention was placed on developing recyclable composite materials that may substitute current petroleum-based goods [48]. Lately, nanocomposites relying on organic biopolymers (such as cellulosic, corn starch, and lactic) have been investigated for a variety of uses, one of which is the food sector for excellent packaging. Bionanocomposites are environmentally acceptable and long-lasting food packaging materials. To summarize, utilization of bionanocomposites for ecological purposes is still an issue for investigators and researchers, but its significance will grow over time owing to the commercialization of bionanocomposites-based products.

6. CONCLUSION

Biopolymers and their composites, which demonstrate to be a more affordable alternative to petro-based polymers, are the foundation of bionanocomposites, which have tremendous promise as prospective renewable resources. Researching sustainable nanocomposite compounds that potentially substitute current petroleum-based goods has already received a lot of attention. Nanocomposites made from organic bio polymers (including starch, cellulose, and lactic acid) are only currently being investigated for a variety of uses. A potential new market is the food business for high-quality packaging. Bionanocomposites are environmentally friendly and sustainable options for packaging food technologies. Conclusion: Although using bionanocomposites for ecological purposes currently presents an obstacle to scientists and investigators, its significance will grow over time as a result of the marketing of goods based on them.

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