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Review

Overview of bacterial cellulose composites: A multipurpose advanced material

Nasrullah Shah[a,b,1], Mazhar Ul-Islam[a,1], Waleed Ahmad Khattak[a], Joong Kon Park[a,*]

[a] Department of Chemical Engineering, Kyungpook National University, Daegu 702-701, Republic of Korea
[b] Department of Chemistry, Abdul Wali Khan University, Mardan, Pakistan

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ABSTRACT

Bacterial cellulose (BC) has received substantial interest owing to its unique structural features and impressive physico-mechanical properties. BC has a variety of applications in biomedical fields, including use as biomaterial for artificial skin, artificial blood vessels, vascular grafts, scaffolds for tissue engineering, and wound dressing. However, pristine BC lacks certain properties, which limits its applications in various fields; therefore, synthesis of BC composites has been conducted to address these limitations. A variety of BC composite synthetic strategies have been developed based on the nature and relevant applications of the combined materials. BC composites are primarily synthesized through in situ addition of reinforcement materials to BC synthetic media or the ex situ penetration of such materials into BC microfibrils. Polymer blending and solution mixing are less frequently used synthetic approaches. BC composites have been synthesized using numerous materials ranging from organic polymers to inorganic nanoparticles. In medical fields, these composites are used for tissue regeneration, healing of deep wounds, enzyme immobilization, and synthesis of medical devices that could replace cardiovascular and other connective tissues. Various electrical products, including biosensors, biocatalysts, E-papers, display devices, electrical instruments, and optoelectronic devices, are prepared from BC composites with conductive materials. In this review, we compiled various synthetic approaches for BC composite synthesis, classes of BC composites, and applications of BC composites. This study will increase interest in BC composites and the development of new ideas in this field.

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Abbreviations: AAc, acrylic acid; BC, bacterial cellulose; Ch, chitosan; CNTs, carbon nanotubes; COL, collagen; EFM, electric force microscopy; FeO, iron oxide; FE-SEM, field emission scanning electron microscopy; FRP, fiber reinforced polymer; GO, graphene oxide; HA, hydroxyapatite; HRP, horseradish peroxidase; MIP, molecularly imprinted polymers; MMT, montmorrilonite; NMMO, N-methy morpholine N-oxide; NPs, nanoparticles; OLED, organic light emitting diode; PAni, polyanaline; PBH, poly-3-hydroxybutyrate; Pd, palladium; Pt, platinum; PVA, polyvinyl alcohol; TEM, transmission electron microscopy; TiO_2, titanium dioxide; XRD, X-ray diffraction; ZnO, zinc oxide.

* Corresponding author. Tel.: +82 53 950 5621; fax: +82 53 950 6615.
E-mail address: parkjk@knu.ac.kr (J.K. Park).
[1] The first two authors contributed equally to this manuscript.

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1. Introduction

Since its discovery, bacterial cellulose (BC) has shown tremendous potential as an effective biopolymer in various fields. The structural features of BC are far superior to those of plant cellulose, which impart it with better properties (Ul-Islam, Khan, & Park, 2012a; Ul-Islam, Khan, & Park, 2012b). Fibril networks consisting of well arranged three dimensional nanofibers enable production of BC sheets with high surface area and porosity (Ul-Islam et al., 2012a). Moreover, the crystallinity and mechanical strength of BC are higher than those of plant cellulose, which has increased its utilization in biomedical and other related fields. Specifically, BC has been applied for wound dressings, burn treatments, tissue regeneration, skin substitutes, catalyst sensing materials, and electronic devices (Ciechanska, 2004; Czaja, Krystynowicz, Bielecki, & Brown, 2006; Czaja, Young, Kawechi, & Brown, 2007). However, lack of antibacterial, antioxidant, conducting and magnetic properties has diminished its capabilities in biomedical and electronic fields (Kim et al., 2011; Maria, Santos, Oliveira, & Valle, 2010).

Polymer composites have enhanced the material and biological properties of pure polymers (Bloor, Donnelly, Hands, Laughlin, & Lussey, 2005; Islam et al., 2011; Maneerung, Tokura, & Rujiravanit, 2007; Qian, 2004). As a result, composites of BC have been synthesized to overcome its limitations and increase its applications. The biomedical efficacy of BC has been increased by synthesizing its composites using bioactive polymers, nanomaterials, and solid particles. BC composites confer antibacterial, antiviral, antifungal, biocompatible, wound healing, conducting, magnetic and optical properties to BC (Evans, O'Neill, Malyvanh, Lee, & Woodward, 2003; Kim et al., 2011; Maneerung et al., 2007; Nakayama et al., 2004; Saibuatong & Philsalaphong, 2010; Shi et al., 2012; Ul-Islam et al., 2012a). Composite synthesis technology has also advanced with the development of new techniques. Currently, BC composites are synthesized through numerous routes based on the nature and size of the reinforcement material. Among the polymers used for composite synthesis, chitosan (Ch), gelatin, and collagen (COL) have been successfully combined with BC to improve its biological properties, while graphene oxide (GO) and polyanaline (PAni) increased the conducting properties of BC (Feng, Zhang, Shen, Yoshino, & Feng, 2012; Shi et al., 2012). Numerous nanoparticles (NPs) including silver (Ag), gold (Au), palladium (Pd), iron oxide (FeO), platinum (Pt) and titanium oxide (TiO_2) have been utilized in BC composites for various applications (Evans et al., 2003; Maneerung et al., 2007; Serafica, Mormino, & Bungay, 2002; Zhang et al., 2010). For example, BC-Ag has been synthesized through numerous synthetic strategies to impart antibacterial activities to BC, which consequently improves its performance when applied for wound healing. BC-Pd, BC-Pt, BC-Au, and BC-FeO have introduced conducting properties to BC sheets that are utilized in biosensors, display devices, electronic papers, security paper, and catalysis (Evans et al., 2003; Maneerung et al., 2007; Zhang et al., 2010).

Since BC has multiple applications, the compilation of fundamental synthetic approaches for enhanced production, environmental issues and industrial needs is of the utmost importance. Moreover, the approaches employed to date to overcome the limitations associated with pristine BC must be known before proceeding toward its practical applications. Accordingly, knowledge pertaining to possible routes of synthesis of BC composites and their consequent pros and cons can lead to the advancement of these materials for specific applications. Critical literature studies conducted to date have revealed that BC composites developmental strategies are governed by the nature of reinforcement materials and the desired application.

Previous efforts identifying the shortcomings of pure BC, stepwise development of BC composites to overcome these limitations and approaches toward the practical applications of BC composites provide a platform for understanding the overall progress in this field to date. In the present review, we have summarized various efforts made to enable inexpensive and enhanced production of BC, various routes developed for synthesizing BC composites, pros and cons of available composite synthesis strategies, classes of BC composites and applications of these composites. To the best of our knowledge, no such comprehensive investigation has previously been conducted for BC composites. Accordingly, this review will provide ideas for the development of novel strategies for preparation of BC composites with specified applications.

2. Composite materials

Composites consist of two types of individual materials, the matrix and the reinforcement material. The matrix acts as a scaffold and supports the reinforcement material, while reinforcements impart physico-chemical and biological properties to the matrix. A synergistic reaction generates material properties that are not present in the individual constituent materials. The broad range of matrices and reinforcing materials allows synthesis of various composite materials with optimized properties. A number of natural and composite materials have been used throughout history; however, the first composite material produced on an industrial scale was fiberglass, which was introduced by Owens Corning in 1935. The combination of fiberglass with plastic polymer produced a much stronger structure that laid the foundation for the fiber reinforced polymer (FRP) industry.

Polymer composites have gained a great deal of attention due to their enhanced physico-mechanical properties and multiple applications relative to the virgin polymeric materials of which they are composed. Reinforcing materials of a different nature such as solid clay particles, metallic oxides, carbonates and fibrous materials have not only strengthened polymers, but also introduced various biological features to polymeric composites (Bloor et al., 2005; Islam et al., 2011; Maneerung et al., 2007; Qian, 2004; Ul-Islam, Khan, Khattak, & Park, 2013). Cellulose has been utilized as