Bacterial Cellulose Nanocomposites

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Abstract Bacterial cellulose (BC) is a biopolymer with high purity of cellulose and excellent mechanical properties. Increased interest in the use of natural polymer makes BC as an excellent alternative for plant cellulose. Although both celluloses consist of unbranched pellicle with chemically equivalent structure, bacterial cellulose exhibits greater properties and potential in wider applications. The structure of bacterial cellulose that consists only glucose monomer and nanosized cellulose fibres secreted by the bacteria induces it to have high water-holding capacity, high crystallinity, high degree of polymerization and high mechanical strength. Furthermore, the characterization of BC can be certainly altered by incorporation with materials that are not essential for the bacterial growth into the fermentation medium. This unique property of BC opens a new gate for the development of new cellulose nanocomposites with desired properties by the incorporation of selective suitable materials. The BC nanocomposites produced opens new opportunity for various usages of BC in different fields of application in the pharmaceutical, chemical, medical and wastewater treatment plants.

Keywords Bacterial cellulose · Bacterial cellulose composites
Nanocomposites · Biopolymer composites

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1 Introduction

Cellulose from bacteria has more advantages than the cellulose found in plants. These advantages provide plenty room for the use of the bacterial cellulose (BC) in various fields. The most significant advantage of the BC compared to plant cellulose is its high purity. The BC from fermentation is produced in a pure form without lignin and hemicelluloses (Tyagi and Suresh 2015). It is highly hydrophilic with high mechanical strength. As BC is 100% pure and produced in hydrophilic matrix forms, its extensive fibrils and high mechanical strength are maintained throughout the formation. The BC can be produced using different methods and substrates whereby the properties can be modified based on the application. Soluble or insoluble materials added in the fermentation medium, such as enzymes and metallic compound, can directly be incorporated in the cellulose network during the synthesis (Serafica et al. 2002). These properties open the opportunities in many fields mainly in medical field, wastewater treatment, paper and also audio industries.

Addition of other materials that are not needed in the growth of bacteria in the fermentation medium is proven to affect the yield and properties of BC (Ruka et al. 2013). This modification was done either by using in situ or ex situ techniques (Shah et al. 2013). Several researchers have shown the ability to improve the production of BC, while others have successfully altered the properties of the cellulose by adding certain substrates or by manipulating the operating conditions. For example, Park et al. (2013) reported that the addition of magnetite nanoparticles and polyaniline enhanced the thermal stability of BC while da Silva et al. (2016) reported that the addition of polyethylene glycol improved hydrophilicity properties of BC.

This unique ability of BC allowing a series of potential applications as a new novel BC composite can be produced with modified properties based on its function. These applications range from high mechanical strength of hydrogel with addition of genipin (Dayal and Catchmark 2016; Nakayama et al. 2004), incorporation of aloe vera as wound dressing (Saibuatong and Phisalaphong 2010), antimicrobial film with addition of silver nanoparticles (Yang et al. 2012; Wu et al. 2014) to the use of BC as membranes such as cellulose acetate membranes reinforced with BC sheet (Gindl and Keckes 2004). Development of electromagnetic nanocomposite with the incorporation of magnetite nanoparticles and polyaniline was reported by Park et al. (2013). Juncu et al. (2015) suggested the novel uses of BC for drug delivery with the addition of carboxymethyl cellulose. Furthermore, Shanshan et al. (2012) demonstrated that the production of BC membrane in *N*-methylmorpholine *N*-oxide had better mechanical and barrier properties.

Undeniably, conservation of the forest, particularly trees, is essential in managing the global warming. However, excessive use of trees for cellulose-based products such as paper, biofuels and construction materials has been continuously depleting the forest resources (deforestation) which lead to global warming problem. At the same time, natural polymers such as cellulose have attracted many attentions due to the effect of environmental pollution of the synthetic polymer (Pei et al. 2013). Previously, plant-derived celluloses were widely used. For example, cellulose fibres have been used as eco-composite plastics in agricultural fields (González-Sánchez et al. 2014), biosorbent for heavy metal removal (O'Connell et al. 2008), nanofiller for biofilm (Salehudin et al. 2014; Slavutsky and Bertuzzi 2014) and other newly developed degradable composites (Piccinno et al. 2015). However, in recent time, BC is started to be used because of its excellent and promising properties (Ashori et al. 2012). Table 1 shows the development of BC and its application starting from dessert or *nata* in the 1990s followed by various other applications throughout the year.

2 Bacterial Cellulose (BC)

BC is a source of cellulose other than plant cellulose. It is produced by bacteria from many genera such as *Acetobacter*, *Achromobacter*, *Agrobacterium and Sarcina*. However, from that many lists of cellulose producers, the only species that is well known with its capability to produce cellulose in large quantity is *Acetobacter* genus. While within that species, *A. xylinus* or *Acetobacter xylinum* (*A. xylinum*) is the one that is being used extensively in research and studies (Jonas and Farah 1997).

A. xylinum produces cellulose from glucan chains. The chains extrude into the fermentation medium from *A. xylinum* pores. These processes are repeated until a bundle of microfibrils is gathered and forms the BC. Medium for BC fermentation can be from any kind of carbon sources or sugars. *Acetobacter* needs oxygen to produce the BC. Therefore, the production will occur mostly at the surface of the liquid (Schramm and Hestrin 1954, Zahan et al. 2014; Hsieh et al. 2016).

The BC pellicle is pure and extremely hydrophilic. Therefore, it needs no treatment which makes its original high mechanical strength retained. These unique characteristics of BC open many rooms for new applications as the properties of BC can be changed by manipulating the fermentation process. The BC has more advantages compared to plant cellulose. The most significant advantage is its purity. The BC has no hemicelluloses or lignin as in plant cellulose; thus, less processing steps are required. Besides, its structure is stronger and finer compared to plant cellulose which is due to longer and finer fibre length of BC. Figure 1 shows a microstructure of BC and plant cellulose at 5000 times magnification.

2.1 Synthesis of Bacterial Cellulose

There are several bacteria which are able to produce cellulose such as the strain from genera *Acetobacter*, *Agrobacterium*, *Pseudomonas*, *Rhizobium* and *Sarcina*. It has superior properties such as ultrafine network structure, high biodegradability

Table 1 Development in bacterial cellulose research

Development	Details	References
1950s Research on bacterial strain, fermentation medium and fermentation condition	Synthesis of cellulose by *Acetobacter xylinum*	Hestrin and Schramm (1954)
	Improved cellulose production using *Acetobacter xylinum* mutant	De Wulf et al. (1996)
	Improved production of cellulose with Acetobacter SP.LMG 1518 in submerged culture	Vandamme et al. (1998)
	Production of BC from fructose in continuous culture	Naritomi et al. (1998)
	Optimization of fermentation condition of *Acetobacter xylinum* in shaking culture	Son et al. (2001)
	Increased production of BC in synthetic media under shaking condition	Son et al. (2003)
	Production of BC from persimmon vinegar	Kim et al. (2006)
1990s Research on characterization of BC	Mechanical properties of bacterial sheets	Yamanaka et al. (1989)
	Characterization of BC produced by *Acetobacter pasteurianus* strain	Bertocchi et al. (1997)
	Characterization on mechanical properties of BC and chitosan blends	Wu et al. (2004)
	Microbial cellulose structure in stationary and agitated culture	Czaja et al. (2004)
	Characterization of water in BC	Gelin et al. (2007)
2000 Research on new application of BC	*Nata de coco* as dessert	Budhiono et al. (1999)
	Electronic paper displays made from microbial cellulose	Shah and Brown (2005)
	BC as wound healer	Czaja et al. (2006)
	Antimicrobial films from BC	Gao et al. (2014)
	BC for skin repair materials	Fu et al. (2011)
	BC as carrier for drug delivery system	Amin et al. (2012)
2009 Research on modification of BC and its application	Modification of BC using nano aloe vera for wound dressing	Saibuatong and Phisalaphong (2010)
	Hybrid BC nanocrystals and silver nanoparticles	George et al. (2014)
	Modification of BC using magnetic field	Fijalkowski et al. (2015)

(continued)

Table 1 (continued)

Development	Details	References
	Modification of BC–alginate composites for scaffold in tissue engineering	Kirdponpattara et al. (2015)
	Surface modification of BC using trimethylsilylation for oil–water separation	Sai et al. (2015)
	Modification of BC structure under ultrasonic irradiation	Paximada et al. (2016)

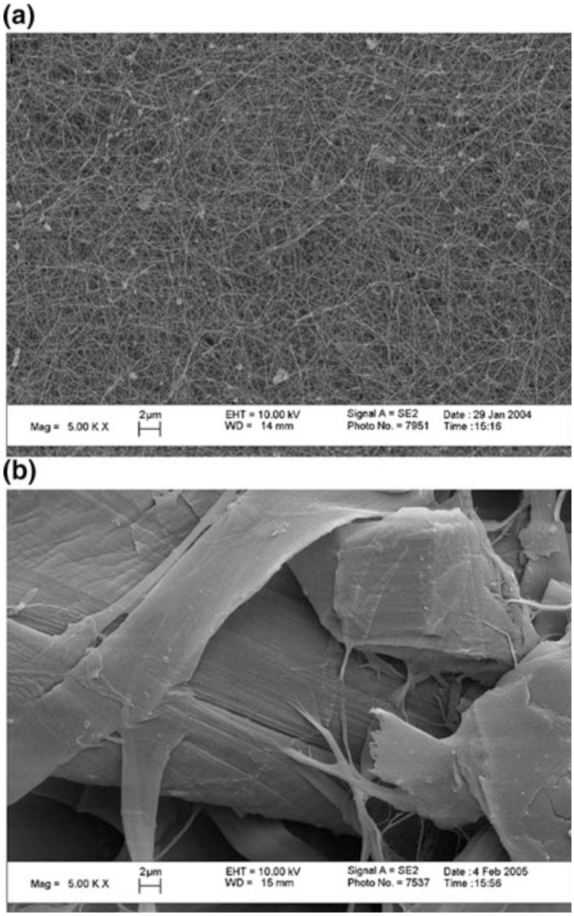

Fig. 1 SEM images of **a** bacterial cellulose and **b** plant cellulose at 5000 times magnification

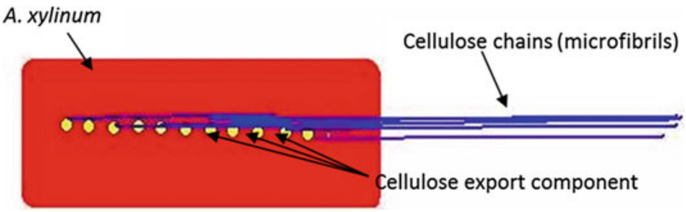

Fig. 2 Secretion of microfibrils by *Acetobacter* cells

and high mechanical strength as compared to plant cellulose (Tsuchida and Yoshinaga 1997). It is expected to be an alternative for biodegradable biopolymer. According to Lee et al. (2002), cellulose synthesized by the bacterium *A. xylinum* and plant cellulose is highly crystalline. However, the arrangements of glucosyl units of the crystallites make them differ to each other.

A. xylinum is acetic acid-producing bacterium which is widely used as the model system to study the enzymes and genes involved in cellulose biosynthesis. This species of gram-negative bacteria has high capability to produce cellulose by converting carbon source such as glucose or sucrose into cellulose. It is well known that *A. xylinum* is an obligate aerobe and forms cellulose at the air/liquid interface in undisturbed cultures. Figure 2 demonstrates the formation of microfibrils by *A. xylinum*.

Multiple cellulose chain or microfibrils are synthesized in the interior of bacteria cell and spun out of BC export component or nozzles (Iguchi et al. 2011). The cellulose synthesis will continue until a limited condition such as when carbon sources are insufficient or when the BC filled the discs in fermentation using rotary discs reactor (Pa'e 2009; Khairul et al. 2016).

Most cellulose-producing acetic acid bacteria can convert glucose into gluconic acid and ketogluconic acid. The enzyme responsible for the conversion of glucose to gluconic acid is membrane-bound glucose dehydrogenase (GDH) (Hwang et al. 1999). This will simply remove glucose from the fermentation medium and avoid the formation of cellulose (Toru et al. 2005).

2.2 *Application of Bacterial Cellulose*

BC has similar chemical structure as plant cellulose, but it has higher purity without lignin or hemicelluloses. Therefore, using BC is more economic compared to plant cellulose because it can skip many stages in the production of pure plant cellulose (Jonas and Farah 1997), thus lowering the production cost. Moreover, its distinguishing properties such as ultrafine nanofibre, biodegradability and high mechanical test (Amin et al. 2012) make it as promising materials for many applications.

The interest on applications of BC grows rapidly since the 1990s. Those applications started with the BC usage in its ordinary form and expand to BC composites *via* the modification of BC using other materials.

3 Modification of Bacterial Cellulose for the Production of Bacterial Cellulose Nanocomposites

The most attractive feature of BC production is the ability to control and modify the properties of the cellulose product while it is being synthesized. Additions of other materials that are not required for bacterial growth to the medium can alter the yield and properties of the cellulose produced (Ruka et al. 2013). With this ability, the chemical composition (Shirai et al. 1994) and properties of BC such as hydrophilicity can be adjusted (Martínez-Sanz et al. 2013). Those improvements are required to enhance the capabilities of BC in order to fulfil the demand in different fields (Shah et al. 2013). The capacity to control and adjust the cellulose characteristic during the synthesis allows the development of new BC composites with better properties than would be conceivable by post-synthetic processing of other sources of cellulose.

Modification of BC to produce BC composites can be done using numerous methods depending on the additives or materials used. The method likewise changes with the required applications. In general, there are two fundamental approaches in modifying BC: ex situ and in situ modification methods.

3.1 *Ex Situ Modification of Bacterial Cellulose*

Ex situ modification method can be explained as the modification of pure BC after the cellulose is harvested (Shah et al. 2013). This involves the impregnation of BC with other materials to produce composites. The interaction might be physical or occur through definite hydrogen bonding between the BC and reinforcement materials. Liquid substances and tiny solid particles can easily penetrate and become engrossed inside the porous BC matrix. A schematic diagram showing the synthesis of BC composites using this method is provided in Fig. 3.

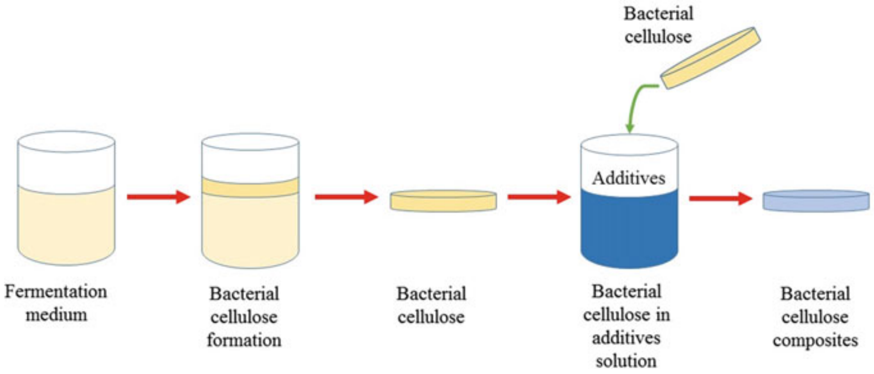

Fig. 3 Modification of bacterial cellulose using ex situ method

The properties of BC are differently affected by the additives used. The major hurdle associated with the ex situ modification method is the size and nature of the additives. Specifically, only submicron to nanosized materials can be impregnated into BC matrix. This is because larger particles cannot enter the BC pores, and hydrophobic materials are not able to combine with BC. Moreover, the structural arrangement of the BC fibril is not always uniform. Therefore, penetrating materials might not be homogeneously distributed inside the BC matrix. Accordingly, there is a need to identify new BC composite synthesis routes to resolve this problem. Table 2 lists previous works on producing BC composites using ex situ modification methods.

3.2 In Situ Modification of Bacterial Cellulose

The in situ method utilizes the addition of other materials as additives to the BC during its synthesis, which then becomes part of the cellulose structure. Using this method, additives were added to BC fermentation medium at the beginning of the process. A schematic diagram showing the synthesis of BC composites using this method is provided in Fig. 4.

Microfibrils of BC become denser with time and produce a web-shaped structure (Horii et al. 1997; Tang et al. 2010) that can trap various materials added to the medium (Ul-Islam et al. 2012). The encaged materials become part of the BC fibril network, resulting in BC composites. Bacterial composites can be synthesized via static fermentation (Wu et al. 2014; Saibuatong and Phisalaphong 2010), agitated culture (Cheng et al. 2009; Yan et al. 2008) and in vessels with rotating discs called rotary disc reactor (Pa'e et al. 2013; Serafica et al. 2002).

In situ modification of BC is a widely used approach that employs a wide range of modifications in agitation equipment and operating methods. However, this technique has certain limitations that prevent the synthesis of many BC composites. For example, several important antimicrobial agents such as titanium oxide cannot be added directly to the media because of their toxic effects on microorganisms. Moreover, BC composite synthesized through agitation culture cannot be applied as a gel or sheet in biomedical applications. Table 3 lists previous works on producing BC composites using in situ modification methods.

3.3 Characterization of Bacterial Cellulose Nanocomposites

BC composites can be characterized in many different ways. These important properties will vary from application to application. Microstructure study of the BC composites will provide information about the appearance of the cellulose produced under microscopic scale. Field emission scanning electron microscope is usually used to study the microstructure of the BC. The FESEM is a versatile analytical

Table 2 Previous works on ex situ modification of bacterial cellulose

Materials added	Impact	References
Polyethylene glycol	• Produced composite with high hydrophilicity which is suitable for biomedical devices • No significant effect to crystalline structure	da Silva et al. (2016)
Conductive polymer complex: poly (3,4-ethylenedioxythiophene)-poly (4-styrenesulphonate) (PEDOT/PSS)	• Development of composites that are suitable for electrodes and temperature sensors • Strong absorption in the red and near-infrared spectral region	Aleshin et al. (2015)
Carboxylmethyl cellulose (CMC)	• Produced CMC-BC composites that are suitable for drug release • Higher swelling rate up to 20% compared to CMC alone without BC	Juncu et al. (2015)
Ionic conducting polymer (ICP): *N*-hydroxyethyl acrylamide and 3-sulphopropyl methacrylate potassium salt	• Produced optically transparent BC/ICP composite with electro-conductive capability • Improved the electrical conductivity of the composite • No further significant increase on optical transparency for impregnated of 2 ICP salt	Jeon et al. (2014)
Polylactic acid (PLA), polycaprolactone (PCL), cellulose acetate (CA) and poly(methyl methacrylate) (PMMA)	• Produced composites with enhanced mechanical properties • Increased Young's modulus for all polymers added with increase of BC in the composites • High surface-area-to-volume ratio	Pircher et al. (2014)
Poly (vinyl alcohol) and chitosan	• Produced composite for release of ibuprofen sodium salt • Decrease of swelling ability with the increase of BC in the composites • Low cumulative release of ibuprofen sodium salt	Pavaloiu et al. (2014)
Polylactic acid (PLA)	• Produced composites films with high water barrier • Decrease of water permeability by 48%	Martínez-Sanz et al. (2013)
Polyaniline (PANI)	• Produced BC composite films with better thermal stability and optimal weight loss (20%) due to degradation • Polymerization of PANI on BC produced dark green film indicating colour of the aniline monomers	Park et al. (2013)

(continued)

Table 2 (continued)

Materials added	Impact	References
Polyurethane resin	• Produced composites that are able to emit light • Suitable as a substrate for organic light-emitting diode (OLED) • Higher degradation temperature up to 350 °C and 8% increase of reflective index compared to polyurethane resin	Ummartyotin et al. (2012)

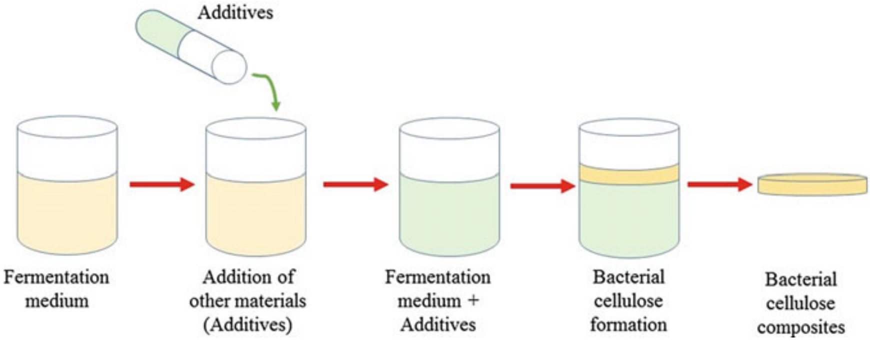

Fig. 4 Modification of bacterial cellulose using in situ method

ultrahigh resolution that extends imaging and analytical resolution beyond previously achievable limits. The equipment is well suited for characterization of BC since it provides high magnification up to 30,000 magnification. Since BC consists of multiple nanocellulose networks, equipment with high magnification like FESEM will provide better overview of the samples. It also has a unique in-lens detector for clear topographic imaging in high vacuum mode.

The possible interactions between the components in the BC composites were evaluated by X-ray diffractometer (XRD) and Fourier transform infrared spectroscopy (FTIR). XRD is routinely employed to characterize the phase composition and per cent crystallinity for organic or inorganic materials. It is important to study the crystallinity patterns of BC and BC composites since it influence many of its characteristics including tensile strength, opacity and its swelling ability.

FTIR identifies chemical bonds in a molecule by producing an infrared absorption spectrum. The spectra produce a profile of the sample, a distinctive molecular fingerprint that can be used to screen and scan samples for many different components. Therefore, FTIR is an effective analytical instrument for detecting functional groups in the BC composites and characterizing the difference between native BC.

Table 3 Previous works on in situ modification of bacterial cellulose

Materials added	Impact	References
Carboxylmethyl cellulose, pectin, gelatine, cornstarch and corn steep liquor	• Produced BC composites with maintained basic network structure with addition of all additives • Increased mechanical properties when pectin, gelatine and carboxylmethyl cellulose were present • Decreased crystallinity with carboxylmethyl cellulose and gelatine as additives	Dayal and Catchmark (2016)
Silver nanoparticle	• Produced antimicrobial wound dressing similar to a commercial silver-containing dressing • No obvious difference in crystallinity • Good antimicrobial effect against *E. coli* and *S. aureus*	Wu et al. (2014)
Poly(3-hydroxybutyrate) (PHB)	• Addition of PHB altered properties of BC film produced • Resulted in decrease of crystallinity by 34% and tensile strength (36%) but increased the cellulose yield	Ruka et al. (2013)
Polyaniline (PANI)	• Produced conductive films from BC-PANI composites • Increased 42% of BC conductivity and electrical sensitivity with addition of PANI	Pa’e et al. (2013)
Magnetite nanoparticles (MNPs)	• Produced BC composite films that have electromagnetic properties • MNP was successfully embedded in the fibre structure • Introduction of MNP enhanced thermal stability of the composite films with degradation temperature of 273 °C	Park et al. (2013)

Tensile properties specify in what way that the materials respond to forces applied in tension. A tensile test is an important test performed to define the modulus of elasticity, elongation and Young’s modulus of native BC and BC composites. In this test, the specimen is carefully prepared and loaded in a very controlled manner while measuring the applied load and the elongation of the specimen over some distance. The results from the testing are used for the selection of materials for various purposes and application considering how it will react under different types of forces.

4 Application of Bacterial Cellulose Nanocomposites in Different Fields

Modification of BC had been done to enhance the properties of native BC and impart some additional properties for certain specific application. A variety of additives materials that had been used lead to the development of many new composite materials design for application on different fields.

4.1 Application in Biomedical Field

The modification of the bacterial cellulose can occur during or after fermentation by introducing selected bioactive material as additive in order to produce bacterial cellulose nanocomposites. This unique nanostructured matrix of composite materials are widely used in biomedical applications (Liyaskina et al. 2017). Modifying bacterial cellulose results in a composite material with better properties such as good mechanical properties and high moisture-keeping properties. These features make modified bacterial cellulose an excellent dressing material for treating different kinds of wounds, burns and ulcers. BC and BC nanocomposites are mostly used in the medical field, including wound healing materials (Legeza et al. 2004; Ul-Islam et al. 2012; Kim et al. 2011), artificial skin, blood vessels (Klemm et al. 2001; Charpentier et al. 2006; Arias et al. 2016), scaffolds for tissue engineering (Watanabe et al. 1998) and drug delivery (Amin et al. 2012; Müller et al. 2013). Table 4 lists different uses of BC nanocomposites in the medical field.

Table 4 Application of BC nanocomposites in biomedical field

Field	Application	Example of additives	References
Biomedical	• Antimicrobial wound dressing	• Chitosan	Lin et al. (2013)
		• Silver nanoparticles	Maneerung et al. (2008)
		• Montmorillonite	Ul-Islam et al. (2012)
	• Scaffold for tissue engineering	• Alginate	Kirdponpattara et al. (2015)
		• Calcium phosphates	Busuioc et al. (2016)
		• Silk fibroin	Barud et al. (2016)
	Hydrogel for controlled drug release	• Carboxymethyl cellulose	Juncu et al. (2015)
		• Graphene oxide	Luo et al. (2017)

4.2 Application in Electronic Device

The uses of BC nanocomposites have been explored as conducting materials for application in electric and electronic devices. These include sensors, electronic, papers and display devices (Muller et al. 2012; Lee et al. 2012). Previous researchers have revealed the production of BC nanocomposites with conducting properties with addition of CNTs (Yoon et al. 2006), graphene (Feng et al. 2012) and graphite nanoplatelets (Zhou et al. 2013) which are well known as conducting nanomaterial. One of the examples of BC conducting polymer composite was prepared by Muller et al. (2011). In their research, pyrrole was added into BC matrix through in situ oxidative polymerization resulted to 1 S/cm conductance for the composites. Another BC conducting composite was also successfully produced from polyaniline (Pa'e et al. 2013; Muller et al. 2011). The BC–polyaniline nanocomposites prepared were reported to have good conducting properties, thus suitable for the uses as electronic device such as sensor, signal receiver and fuel cell and to guide enviable cell function for tissue engineering applications. Table 5 shows some application of BC nanocomposites in electric and electronic fields.

4.3 Application in Wastewater Treatment

In wastewater treatment, BC with its unique properties is suitable to be used as adsorbent for heavy metal removal (Wang et al. 2015; Lu et al. 2010). This includes

Table 5 Application of BC nanocomposites in biomedical field

Field	Application	Example of additives	References
Conducting materials and electronic devices	• Electronic paper and E-book	• Refined cellulose	Mormino and Bungay (2003)
		• Dichromate dyes	Shah and Brown (2005)
	• Batteries	• Palladium	Evans et al. 2003
		• Polypyrrole	Zhang et al. (2015)
		• Molybdenum disulphide	Zhang et al. (2016)
	• Electric and electronic instruments	• Titanium dioxide	Gutierrez et al. (2012)
		• Graphite	Kiziltas et al. (2016)
		• Polyaniline	Hu et al. (2011)
	• Biosensor	• Gold	Li et al. (2011)
		• Platinum	Foresti et al. (2017)

Table 6 Bacterial cellulose as biosorbent for heavy metal removal in wastewater treatment

Biosorbent	Preparation method	Adsorbate	References
BC coated with polyethylenimine	Ex situ	Copper Lead	Wang et al. (2015)
Amino-BC	Ex situ	Lead Cadmium Copper	Lu et al. (2014)
Ammonium sulphamate-BC	Ex situ	Chromium	Lu et al. (2013)
Spherical iron oxide-BC composite	Ex situ	Lead Manganese Chromium	Zhu et al. (2011)
Carboxymethylated-BC	In situ	Copper Lead	Chen et al. (2009)

high tensile strength, porous structure and high water-holding capacity. Besides that, BC has large surface area with many hydroxyl groups in the chain that make it effective for the separation of heavy metals ions (Lu et al. 2013). Most importantly, BC is simple to produce and the modification can be done using various materials and methods. Furthermore, the physiochemical properties of this BC can be controlled by changes in growth conditions or by chemical modification to obtain desired functionality (Pa'e et al. 2011; Sokolnicki et al. 2006; Serafica et al. 2002). These features along with its biocompatibility and low production make BC ideal to be used as eco-friendly biosorbent for heavy metal removal.

However, the BC itself as biosorbent has several disadvantages such as low adsorption capacity, poor selectivity and high hydrophilicity which makes it swell easily in water. Therefore, new functional group is added to BC to modify its properties and improve the activity of BC on adsorption of heavy metal ions in wastewater treatment. Table 6 lists the previous works on the use of BC as biosorbent for heavy metal removal.

5 Conclusion

BC is a unique material; hence, research and development in BC has expanded fast. This expansion of the BC exploration is due to several advantages such as BC's properties which are suitable for numerous application, easy production process and economical viability. From the foregoing review of the literature, the progress in BC studies continues with its application as nanocomposites. Various synthetic and organic materials were added in situ or ex situ to produce nanocomposites materials with certain properties. At present, the focus is essentially moving towards the reasonable uses of BC and BC nanocomposites as a based material for various medical devices, electronic devices and biosorbent for heavy metal removal.

Various uses in many fields are expected to increase the demand on BC and BC nanocomposites production. Thus, efforts that focus on large-scale production need to be highlighted next.

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