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A Mini review on

Current Advancement in Application of Bacterial Cellulose in Pulp and Paper Industry

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Abstract

Bacterial cellulose (BC) is a nano-biomaterial which is environment friendly and has gained attention in pulp and paper industry. The reason behind its popularity lies in its stout physical properties. BC has high water retention capacity, chemically and mechanically stable, biocompatible, crystalline, ultrafine network structure and has large surface area. The composition of BC consists of glucan molecules arranged linearly with hydrogen bonds. This structure seems indistinguishable from plant cellulose. Unlike other conventional, synthetic or natural cellulose, BC functions well in the field of biomedicine, paper making, nanofillers, water treatment etc. due to its above-mentioned properties. Pulp and Paper industry is one of the sector where sustainable and environment friendly approach becomes the prime need. Potential application of BC in paper industry can include strengthening of paper, increase water holding capacity of paper, formation of electronic papers and in making of flame resistant paper. In this review potential applications, current status and physicochemical properties of BC in pulp and paper technology are discussed.

Keywords: *Bacterial Cellulose; Pulp and Paper; Nano-Biomaterial; Plant Cellulose; Biocompatible.*

1. Introduction

The environmental concern caused the research scientists to focus more on bio based resources, which are imperishable in nature. The film forming properties of microbial polysaccharides such as Bacterial Cellulose (BC) makes them a potential source for several bio and non-bio based sectors of today's world. In contrast to plant cellulose the absence of lignin and hemicellulose makes it an inert and biocompatible material. Besides this, BC is biodegradable and safe polymer which is neutral for human consumption. Nanofibrillar structure of BC increases its surface area and makes it porous and a tough polymer at the same time. Because of its versatile nature BC can be modified and produce compounded materials with improved properties (Shah and Brown, 2005; Klemm et al. 2006; Hong and Qiu, 2008; Kurosumi et al. 2009; Zeng et al. 2011).

Traditional BC formation methods have proposed by various researchers and their facet of work based on lab-scale and large-scale production of bacterial cellulose. Recently, remarkable progress in production of BC has been observed and various research reports have also been published on use of BC in paper, pharmaceutical and cosmeceutical industries. There are various bacteria that produce cellulose out of which *Gluconobacter xylinus* is most common among them due to its high yield. (Nguyen et al. 2008).

BC is highly pure, thermostable, durable and consistent in nature (Yoshinaga et al. 1997; El-Saied et al. 2008). These features have led the scientist to focus the research towards the use of BC as a new alternative in paper forming and modulating process (Jonas and Farah, 1998; El-Saied et al. 2004; Chawla et al., 2009; Cheng et al. 2011). Potential application of BC in paper industry include strengthening of paper, increase water holding capacity of paper, formation of electronic papers and in making of flame resistant paper. This review describes the potential use of BC in pulp and paper industry.

2. BC based modifications of Paper

The credit of stability and longevity of pulp when it is converted to paper goes to BC which can act as a binder in paper. The reason for this is its structure, which has tiny bundles of cellulose microfibrils (Brown, 2004). The use of BC in paper making has been implemented by Ajinomoto Co. and Mitsubishi Paper Mills in Japan (Hioki et al. 1995). It was observed in a study that when fragmented BC is added to paper pulp, it gives good tensile strength to the paper which is formed out of it (Yamanake and Watanabe, 1995).

2.1 BC for enhancing strength properties of paper

A study demonstrated that by mixing cationic starch or paper pulps to BC shown to improve film properties for enhance packaging strength. Addition of 30 wt.% pulp with short fibers to BC have shown improved mechanical strength, while 2% w/w cassava starch with BC have shown to improve burst, tensile strength, resistance to water vapor and permeability of Oxygen (Pradipasena et al. 2018). Surma-Ślusarska et al. (2008) reported the potential of modifying paper properties by addition of BC to fibrous paper pulps. For this, three different composition have made, in the first one BC synthesised by *Acetobacter xylinum* in medium containing fiber semiproducts from papermaking process was used; in the second one suitably disintegrated bacterial cellulose film was added to the papermaking pulps; and the third one involves attaching semi-product paper sheets with bacterial cellulose film by placing them on a sheet of paper to let it dry drying using Rapid-Koethen method (Surma-Ślusarska et al. 2008). The comparison and determination of fibrous semi-products and their composites with bacterial cellulose was done on the basis of structure and strength. It was noticed, among others, that first two methods are good for the production of composites and these composites show more tensile and dynamic strength than other semi-products for composite preparation (Fig. 1). On comparing two-layered composite (i.e. fibrous semi-product and bacterial cellulose) with bacterial cellulose then the two layered shows

higher tear resistance and peaked static strength in case of comparison with unbeaten pulp (Surma-Ślusarska et al. 2008). The semi product formed by joining the bacterial cellulose and pulp fibres has high mass per unit volume in natural state regardless of the joining method. Pure birch and pine pulps have lower breaking length as compared to the composites of BC, pine pulp, bleached birch and unbeaten pulp.

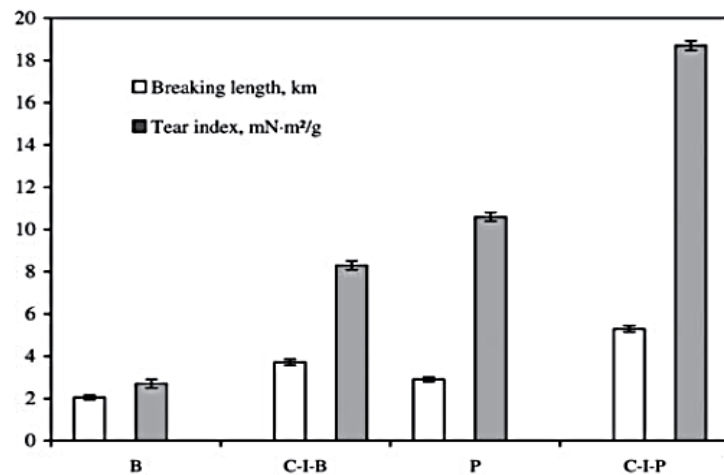


Fig. 1. Strength Property comparison (Breaking Length and Tear Index) of B - Birch Pulp, C-I-B – Composite of BC and Birch Pulp, P – Pine Pulp, C-I-P – composite of BC with Pine Pulp (Adapted from Ref: Surma-Ślusarska et al. 2008)

A study by Rattanawongkun et al. (2019) have made reinforced bagasse (BG) sheets by mixing it with BC. *Komagataeibacter nataicola* culture was used to produce BC, further the BC fibers were defibrillated by using microfluidizer. After studying the physical, tensile and morphology of the reinforced sheet, it was found that BC when mixed with BG has increased the overall density but decreased the porosity of the sheets. SEM images has clearly shown (Fig. 2) that BC fibers have bridged the gaps generally found in BG fibers which is the main cause of increasing strength of the mixed fibers (Fig. 3). There is 117% and 47% enhancement in elongation and tensile strength of the reinforced sheets after just mixing of just 5 wt% BC (Fig. 4) (Rattanawongkun et al. 2019).

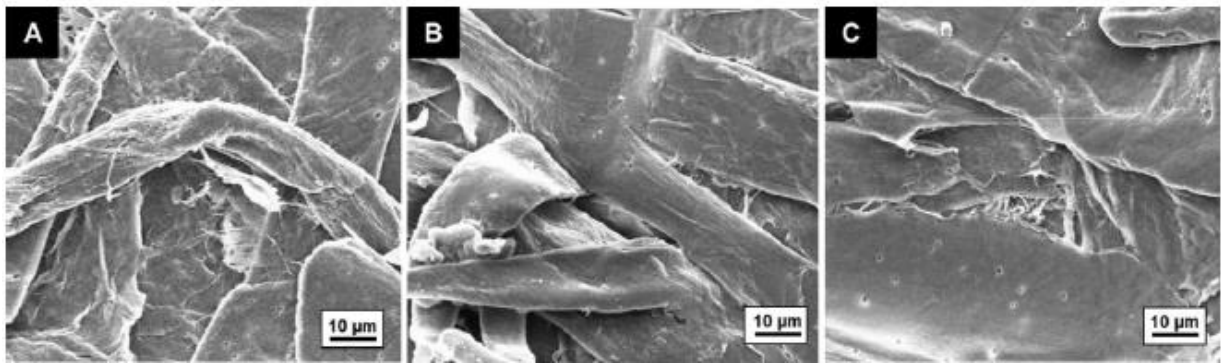


Fig. 2. SEM images of Bagasse sheet containing (A) 0%, (B) 0.5%, (C) 5% of Bacterial Cellulose. (Adapted from Ref: Rattanawongkun et al. 2019)

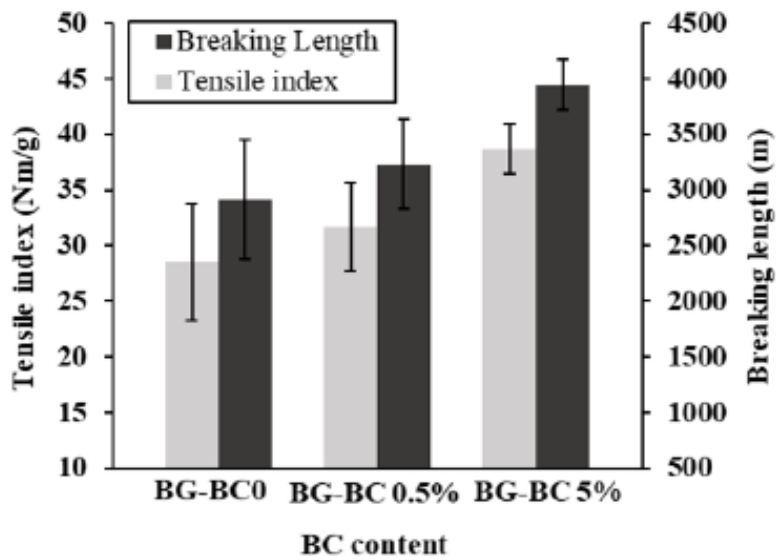


Fig. 3. Reinforcing effect (Breaking Length and Tear Index) of Bagasse sheet containing (A) 0%, (B) 0.5%, (C) 5% of Bacterial Cellulose. (Adapted from Ref: Rattanawongkun et al. 2019)

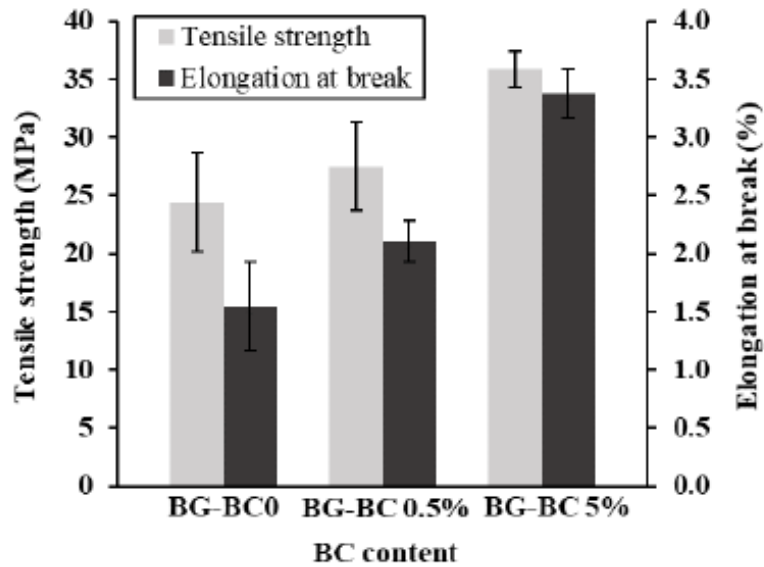


Fig. 4. Reinforcing effect (Tensile Strength and Elongation at Break) of Bagasse sheet containing (A) 0%, (B) 0.5%, (C) 5% of Bacterial Cellulose. (Adapted from Ref: Rattanawongkun et al. 2019)

Papers made up of recycled fibres can be strengthened using BC fibers. Xiang et al. (2019) in their study proved that carboxymethyl cellulose, xylan, cationized starch, glucomannan and polyethylene oxide were used to upgrade the diffusion of BC fibers. Paper made with the combination of BC fiber and recycled fiber showed an increase in dry tensile index of 4.2 N.m/g or 12.7%, obtained by addition of glucomannan. When glucomannan adsorption on BC fibers was studied, a high colloidal stability of BC fiber suspension with no signs of aggregation and enhanced wet tensile index was seen (Xiang et al. 2019).

In another study, an enhancement in tear and tensile index by 14.2% and 12.2% respectively was exhibited in papers that were produced with pulps that were cultivated in agitation process (Campano et al. 2018), thus the paper flexibility was increased as well. Whereas, in static culture enhanced pulps fail to improve the paper's tensile index while increasing the tear index by 12.4%. The mechanism of production of both types

had been proposed. The primary fibers were coated by bacteria in agitated culture, thus improving their quality. Heterogeneous systems were found in static culture. This is because of the sedimentation of recycled fibers during the movement of bacteria to the culture broth's surface in the need of oxygen (Campano et al. 2018). Hence BC's production in situ with recycled fibers can hence be an alternative which replaces conventional paper strengthening agents. The results obtained indicate that upgraded pulps production in situ can be performed in paper mills that cultivate pulp streams which can be sterilized through non-exhaustive, low cost operations such as UV or ozone radiation (Campano et al. 2018).

Further a study was done to know the ability of bacterial cellulose on modifying pulp characteristics which was obtained from recycled waste papers (Kalyoncu and Peşman, 2020). During Kombucha tea fermentation, bacterial cellulose was produced. The wet films of bacterial cellulose were dispersed and added at different rates of 5%, 10%, 15% to the waste papers that were recycled. The FTIR, SEM and thermogravimetric analyses were carried out whose values were used to determine the pulp sample characteristics. The tensile and burst index values were maintained constant whereas the value of tear index was partially decreased with increase in bacterial cellulose amount. After thermal aging, the papers that were reinforced with bacterial cellulose did not have any change in the values of brightness, whereas yellowness values have limited change. Higher rates of water absorption and lower values of air permeability were obtained from recycled paper sheets that were reinforced with bacterial cellulose. Considering physical and mechanical properties of bacterial cellulose reinforced paper, a promising alternative is represented by bacterial cellulose (Kalyoncu and Peşman, 2020).

2.2 Fine Quality Papers

Some studies have shown that BC pellets taken from agitated culture were used to form fine quality paper. Bacterial cellulose can be added as a wet-end material during the papermaking process. A study to produce high quality biodegradable fiber was done by forming a composite of sugarcane bagasse and BC (Costa et al. 2020). For this process, the bagasse was first grinded, washed and further hydrolysed to separate cellulose fibers. Then the bagasse fiber was mixed with BC fiber and were further kept for drying. The final composite mixture was then characterised by TGA, DRX and FTIR, and it was found that the quality of the new composite is as good as a rigid and dense paper. This method not only reduces chemical load but also have totally reduced high water consumption to produce same type of material. Resulting pulp is eco-friendly produced from bio-waste from sugarcane industry and have shown high quality, biodegradable and high purity cellulose material (Costa et al. 2020).

2.3 Degraded paper restoration

One of the significant challenges in today's world is to preserve the documentary heritage. Boosting the strength of paper is an important characteristic of bacterial cellulose (BC) which can be exploited to rebuild the old papers which are degraded, this has been showed by a study (Santos et al. 2016). This test was conducted first on the papers with known fibre composition. For this study, the characterization of deteriorated papers was performed followed by reinforcement and then the characterization was done once again. This methodology was applied on Japanese paper (JP), which is a material that is used by conservators, to differentiate between both the materials as reinforcement. The mechanical properties of paper lined with BC and JP were found to be equivalent. Papers lined by using BC have modified optical properties than those reimposed with JP. Also, letters are clearer in the books lined with BC. Only the papers reimposed with BC exhibit changes in pore size. Decrease in burst index also

observed due to aging process. This study provided information that BC improves degraded paper quality, without making any change in the properties in it, and this improvement remains for a long time. These are the reasons why we should opt for BC (Santos et al. 2016).

2.4 Fluorescent Paper

The principal method of coating fluorescent substances to produce fluorescent paper onto the bases of paper has the problem of poor durability and low efficiency. The nanoporous structure of BC can be used to improve the stability of fluorescent particles. Zhang et al. (2019) used a novel method by making complex of Europium (Eu)/BC first and processing cellulosic fibers and complex into paper sheets thus producing fluorescent papers. Stable complex of Eu/BC can be formed by BC in this composting method through its nanoporous structure while the cellulosic fibers which are plant based reduce the stiffness and the cost to the materials. The fluorescent paper showed a great efficiency and fluorescent property. There was an increase in fluorescent intensity or the UV absorbance of EU/BC based fluorescent paper with Eu-BC content increase. After 200 times of folding the fluorescence intensity decreased only by 0.7% which proves the fact that EU/BC based fluorescent paper has great durability and stability (Zhang et al. 2019).

2.5 New Value-Added Products

Bacterial cellulose has been combined with wood cellulose by Fillat et al. (2018) order to obtain biomaterials that have increased barrier properties. Different parameters were assessed for this purpose i.e. two types of combined biomaterials (bilayer and composite) and two different drying temperatures (room temperature and 90 °C). The study has used two bacterial strains (*Gluconacetobacter sacrofermentans* and *Komagataeibacter xylinus*) to produce BC, while eucalyptus paper and filter paper was

used to hold bacterial cellulose (Fig. 5). Increased barrier properties papers were obtained by the BC addition to every one of the paper supports. Higher improvements due to the filter paper's lower initial barrier properties were produced in this kind of paper. Smoother surfaces provided by BC with higher gloss without any detrimental effect. The use of *K. xylinus* gave higher resistance to absorption of water due to its long sized fibers than the fibers from *G. sucrofermentans*, as analysed by scanning electron microscopy (Fillat et al. 2018). Gloss and smoothness were especially increased in the biomaterial's bilayer although in the composite resistance to water and air was further improved. In this type of biomaterial high temperature drying had detrimental effect. Obtained products were analysed through SEM and showed an intimate contact among wood paper and BC fibers. Results obtained reveal the contribution of BC to improve the paper properties and its potential in making new value-added products (Fillat et al. 2018).

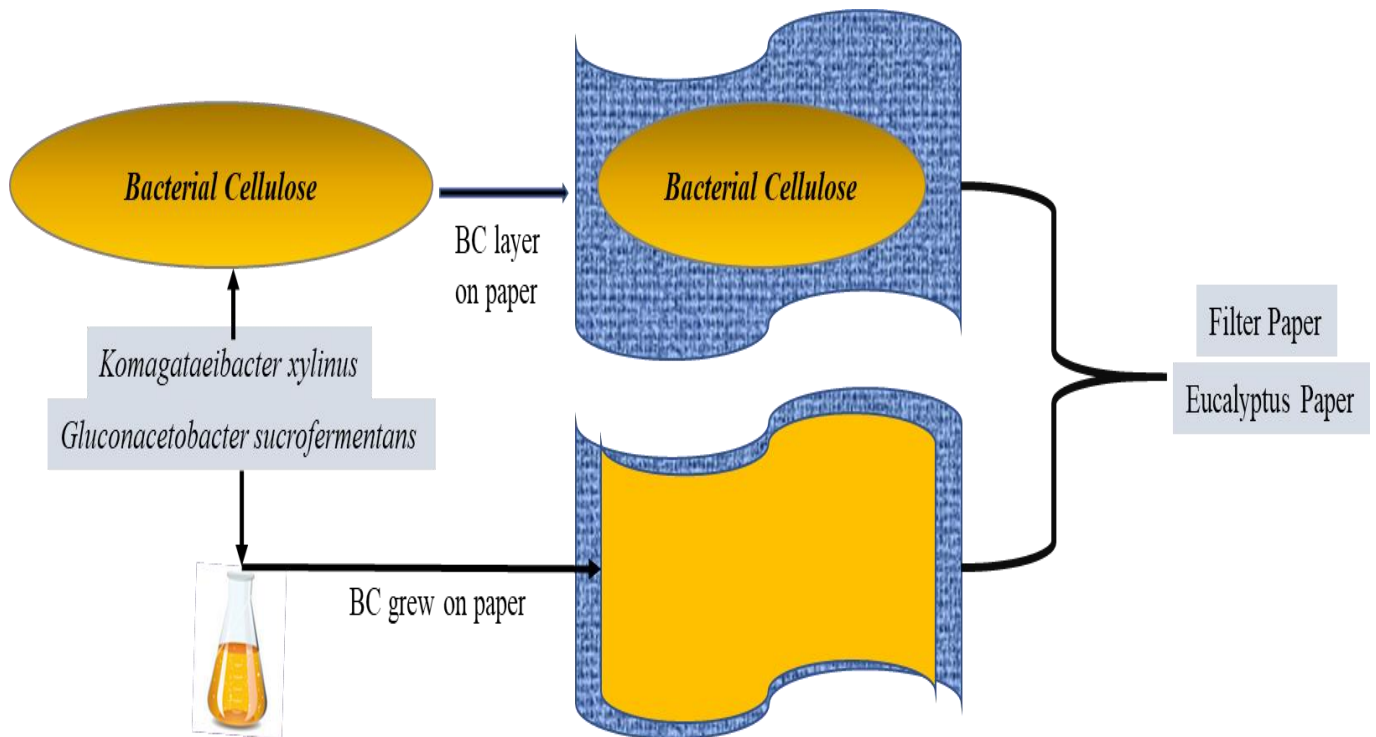


Fig. 5. Concept for use of Bacterial cellulose for increasing barrier properties of paper products

2.6 Composite papers

The comparison of BC based composite paper and pure pulp paper was studied by Iguchi et al. (2000), it was noticed that the folding tolerance of composite paper increased by four folds after the addition of 15% BC also the Young's modulus increased from 2-3.5 (GPa). In the assessments done by Cheng et al. (2011), it was seen that carboxymethyl cellulose-bacterial cellulose composite paper (CMC-BC) showed high mechanical strength, high Young's modulus and tensile strength than ordinary paper. BC is also contributing in the manufacturing of banknotes and bible papers (Iguchi et al., 2000) because these paper products are used for longer duration.

2.7 Conductive papers

Apart from these manufacturing of conductive papers can also involve the use of BC due to the stupendous physical properties it provides to the paper like flexibility, elevated reflectivity, light weight, ease of motility and broad viewing angles (Shah and Brown, 2005). Similarly, an in situ oxidative polymerization of aniline was done by Hu et al. (2011) to produce a group of nanostructural membrane of polyaniline /bacterial cellulose (PANI/BC). In 2012 Gutierrez et al. assessed the conductive characteristics of TiO₂ nanoparticles and TiO₂/bacterial cellulose hybrid inorganic/organic fibers.

2.8 Specialized Fire-Resistant Papers

Basta and El-Saied (2009) reported that BC can be used as flame retardant, *Gluconacetobacter* subsp. *Xylinus* was used to produce this type of BC and glucose was replaced by glucose phosphate in the cultivation medium as the carbon source and for nitrogen source corn steep liquor was used. The processing technique which was investigated did not cause any unacceptable effluents or any toxic chemicals that could pollute the surrounding hence making the process safe for the environment. Using non-isothermal TGA and DTGA the fire retardant behaviour of BC was studied. Methods

like least square method and Coats–Redfern equation were used to estimate the degradation order and the activation energy of each stage of degradation (Basta and El-Saied, 2009). Thermogravimetric analysis, optical properties and strength of BC-phosphate that was added to added paper sheets were tested as well. It was confirmed that glucose along with glucose 6 phosphate was significant in the production of high yield of PCBC1 (phosphate containing bacterial cellulose). Incorporation of 5% of phosphate containing bacterial cellulose with wood pulp during formation of paper sheet was found to improve strength, fire resistance properties and kaolin retention significantly as compared to BC incorporated paper sheets (Basta and El-Saied, 2009). This modified bacterial cellulose is thus a valuable product for the specialized paper preparation in addition to its filler aid function. This study majorly focusses on production of BC in situ in pulps that are recycled to increase the fiber quality in the suspension. The effect of dosages on different levels of the pulp on the optical, physical mechanical properties of handsheets was estimated (Basta and El-Saied, 2009).

3. Conclusion

Researchers across the world are considering BC as a promising material which can be used to make products keeping sustainable development in mind. Though already been used in various sectors, now studies are focusing in its use in Paper sector. Over plant cellulose, BC has many advantages. For producing BC no need to cut trees, it is highly pure and can be blended with plant cellulose as well. Already many researches are going on and have reported vast potential of application of BC in Pulp and Paper industry. It has shown to enhance strength properties of paper when mixed with proper ratio. Also, studies have reported BC use in forming enviormnetal friendly Biomaterials, value-added products, fine papers, fire resistant paper, nanofibers, flexible magnetic paper, electronic papers and new Bio-composites. Therefore, future is bright for the application of BC in Paper sector for enhancing pulp and paper quality, to reduce chemical ad water load, to make new environment friendly materials.

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