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ADDITIVES AND BACTERIAL CELLULOSE (BC): FRIEND OR FOE?

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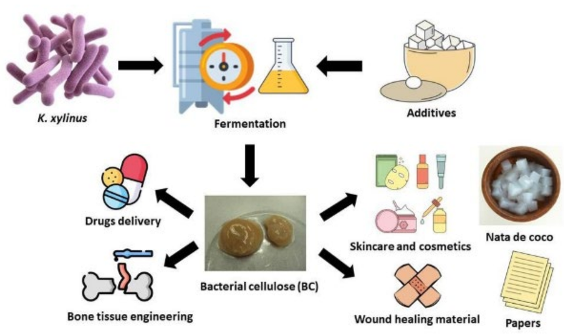
Graphical Abstract



Abstract

In recent years, the issues of environment and economy have encouraged researchers to channel their research interest to sustainable bio-resource. Bacterial cellulose (BC), which is the extracellular matrix from various genera of bacteria is the versatile biopolymer and have unique characteristics. BC had contributed outstanding applications in various fields such as bone tissue engineering, drug delivery, wound healing material, skincare and cosmetics. Numerous researchers have published their studies on BC production to date. In order to further evolve the application of this biomaterial, notable progress towards bacterial cellulose development and its properties enhancement have appeared recently. The establishment of bacterial cellulose in diverse applications has been the subject of numerous papers and research reports. This review paper will elucidate the utilization of various additives that have been employed in BC production and applications. Furthermore, to highlight the important influences of different additives on BC production and qualities in the creation of value-added products.

Keywords: Bacterial cellulose, additives, properties, production, applications

Abstrak

Dalam tahun-tahun kebelakangan ini, isu alam sekitar dan ekonomi telah menggalakkan para penyelidik menyalurkan minat penyelidikan mereka kepada sumber bio yang mampan. Selulosa bakteria (BC), yang merupakan eksopolisakarida daripada pelbagai genera bakteria adalah biopolimer yang nyata dan mempunyai ciri-ciri yang sangat baik. Selulosa bakteria telah menyumbang aplikasi cemerlang dalam pelbagai bidang. Ramai penyelidik telah menerbitkan kajian mereka mengenai pengeluaran selulosa bakteria sehingga kini. Untuk mengembangkan lagi aplikasi biomaterial ini, kemajuan ketara ke arah pembangunan selulosa bakteria dan peningkatan sifatnya telah muncul baru-baru ini. Terdapat banyak penerbitan dan laporan saintifik mengenai penubuhan selulosa bakteria dalam pelbagai aplikasi. Kertas kajian ini akan menjelaskan penggunaan pelbagai bahan tambahan yang telah digunakan dalam pengeluaran dan aplikasi selulosa bakteria. Tambahan pula, ianya dapat menonjolkan kesan ketara pelbagai bahan tambahan ke atas penghasilan selulosa bakteria dan sifat dalam pembangunan produk nilai tambah.

Kata kunci: Selulosa bakteria, bahan tambahan, sifat, pengeluaran, aplikasi

1.0 INTRODUCTION

Cellulose is a polysaccharide, which are the most abundant biopolymer on Earth. It is linked by β-1,4 glycosidic bonds. Most of the cellulose is synthesised by vascular plants, but there are also some microorganisms such as *Komagateibacter, Azotobacter, Sarcina and Rhizobium* that synthesized bacterial cellulose (BC), which resembles to plant cellulose in characteristics [1].

A study by Swingler *et al*. (2021), [5] has reported one of the most plentiful biomaterials that can be found in nature is cellulose, which, it can be found in all plants and being synthesized by several microbial organisms. Meanwhile, [6] stated the extracellular polysaccharides called cellulose are produced by higher plants, lower phototrophs and some microbes from different taxa such as *Acetobacter, Achromobacter*, *Alcaligenes*, *Aerobacter*, *Agrobacterium*, *Azotobacter*, *Rhizobium*, *Pseudomonas*, *Sarcina*, *Dickeya* and *Rhodobacter*. The most prominently discussed in literature as BC producer is genus *Komagataeibacter* (formerly known as *Gluconacetobacter*. This extracellular gelatinous pellicle was first discovered by A. J. Brown in 1886 as "a sort of moist skin, swollen, slippery and gelatinous pellicles" [7]. Blanco *et al*. [18] also mentioned that microorganisms created translucent jelly-like foods by fermenting coconut water, and that this process was first made popular in the Philippines in 1973.

Cellulose has a variety of uses, from being used in the pulp and paper and pharmaceutical industries, cellulose also being used as a renewable source of energy. [2]. According to Lahiri *et al*. (2021), obtaining pure cellulose substrate from plant is challenging due to its association with other biogenic products such as pectin, lignin, hemicellulose, and other compounds found in plants. In comparison with plant cellulose, BC itself has meets the requirements as sustainable eco-friendly biopolymer owing to its production. Furthermore, this extracellular biopolymer is produced in high purity, free off contaminants such as lignin, pectin and hemicellulose [3], that makes this biomaterial being highlighted as an important role in human daily life [4]. In addition, Ullah *et al*., (2016) had mentioned the importance of biopolymers in food, personal care and medical industries are undeniable.

The bacteria that produce this pellicle was first described by Azeredo and colleagues [8] a year earlier and has since been reclassified as *Komagateibacter xylinus*, formerly known as *Gluconacetobacter xylinus*. It was named in recognized of Dr. Kazuo Komagata for his contribution to the bacterial systematics of acetic acid bacteria [9]. Bacterial cellulose (BC) is cultivated under agitated and static fermentation. Static fermentations are straightforward and lead to the appearance of cellulose membranes on the surface of the culture media. However, it was inhibited in industrial implementation as it is high in production cost while agitated fermentation might cause to higher cost-production of BC. The working conditions can be improved to potentially lower manufacturing costs [10]. BC pellicles that have been synthesised are frequently generated as distinct particles. By using multiple additions and varied fermentation conditions, BC's network structure in the fermentation medium can be changed. According to reports, acetic acid bacteria (AAB) produce BC as a UV defence mechanism and to aid in the movement of microorganisms at the liquid's surface in order to fix the required supply of oxygen [11].

The extracellular bacterial cellulose is synthesised by cellulose-producing bacteria, which cultured in a fermentation medium consists of various carbon and nitrogen sources [12] , also unlike plant-based cellulose, which contains by-products like pectin, lignin, and hemicellulose, bacterial cellulose is free of these substances [13]. Due to its distinctive properties, including superior crystallinity, high water holding capacity, high biocompatibility, high mechanical strength, and high degree of polymerization, BC has contributed to a variety of applications. Due to its impressive water retention capability and higher tensile strength, BC has become an essential ingredient in the production of items such as high fidelity acoustic speakers, dessert foods and papers [14]. However, the increasing in production yield of BC is still a tough problem that restrains its applications in various fields such as biomedical, food and paper industry, cosmetics and tissue engineering [15]. Based on the distinctive qualities of the bacteria and the fibre itself, Li and colleagues [16] claimed that cellulose production was still low in 2021. Although 30 strains of bacteria that make cellulose were identified in the study, numerous studies have been done to boost BC production by improving culture conditions, culture modes, and metabolic engineering techniques. Numerous researches have been attempted to increase BC productivity and output because the primary challenges in its manufacturing are its high cost and low yield. They include the utilization of agrowaste, low-cost carbon sources and nitrogen sources and also addition of certain additives. However, limited reports are available on the utilization of various additives on bacterial cellulose yield and productivity from *Komagataeibacter xylinus.* Therefore, this study was aimed to highlight the correlation between additives and the BC in terms of its production and properties. [17] proved that the properties of BC rely on various factors, including the bacterial kind, the fermentation environment, and the nutrients in the growth media. Several parameters, including crystallinity, strength, degree of polymerization, and hygroscopicity, have a substantial impact on the properties of the biopolymer, according to the same study. Figure 1 shows chemical structure of cellulose.

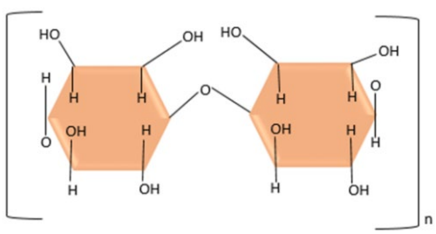


Figure 1 Chemical structure of cellulose

2.0 APPLICATIONS OF BC

The species *Gluconacetobacter xylinus* is well known for its capable to generate bacterial cellulose on a trade scale [18]. *Komagateibacter xylinus* (which is previously known as *G. xylinus*) is the common strain used microorganism in both basic and applied studies for bacterial cellulose manufacturing due to its impressive productivity and has the potentiality to utilize different types of sugars and other compounds as carbon sources [4]. BC from this strain has most recently been employed with other materials in biomedical and tissue engineering, among other fields [19]. As reported by Kolesovs & Semjonovs (2020), [11] BC is well-known with its intrinsic features such as high water retention capacity, hydrophilicity, excellent crystallinity, ability to take on a variety of forms, outstanding biocompatibility, and being extremely pure and long-lasting. Furthermore, bacterial cellulose, unlike plant cellulose has a smaller size in diameter of fibres, thus it leads in greater hydrophilicity [17].

The fibrous-network structure of the BC can be used as a foundation for composite materials, offering scaffolds further benefits including flexibility, hydrophobicity, improved mechanical strength, and antibacterial, magnetic, and conductive properties that are not present in the BC itself. BC is used in the culinary sector to make coconut gel (also known as *Nata* or *Nata de coco*), to extend shelf life and act as an antibacterial food coating. Additionally, it is a beneficial supplement for people with diabetes, obesity, gastrointestinal disorders and cardiovascular diseases [19, 11]. BC is considered as a derivation of pure cellulose that is usually synthesised by the bacteria. As reported by Lahiri *et al*. (2021), [2] due to its impressive purity and unique physicochemical features, it has extensive implementations in numerous industries such as bio-medical industries, food sectors, and for the formation of bio-based polymers and nanocomposites. BC exhibits a great potential in various biomedical applications such as artificial skin, dental implant, wound dressing, haemostatic materials, drug delivery, vascular grafts scaffolds for tissue engineering, biosensor and diagnosis [20]. The high biocompatibility and purity of BC have becoming the essential in biomedical applications. BC films that attached to the skin as wound dressing can provide a good environment for skin regeneration, and also BC is popular in cosmetics as a natural skincare solution for facial masks and scrubs due to its moisturizing properties and non-toxicity [11].

3.0 ADDITIVES IN BC INDUSTRIAL APPLICATIONS

Based on study conducted by [21] high production cost of BC are the major obstacles that inhibit the application of BC in industries. The cost-effectiveness of BC could be improved by using industrial waste and by-product streams as a fermentation medium. Many studies have emphasized on enhancing the cost-effectiveness of cultured media, such as sugarcane juice, coffee cherry husk extract, pineapple peel and corn steep liquor as a less expensive carbon sources and nitrogen. Although BC is well-known as a versatile biopolymer and possessed of numerous advantages over plant cellulose, the production is somewhat costly owing to the high cost of fermentation media and unproductive bacterial strains [22]. When glucose was used as a carbon source, gluconic acid started to develop in the bacterial cellulose culture medium, lowering the pH and yield [23]. Castro and co-workers proposed buffers can be added to the fermentation medium to enhance BC production [24]. The inclusion of additives in the fermentation medium, which are not specifically required for bacterial growth, also can affect the cellulose production [25].

In order to lessen the productional cost of BC, various natural carbon sources beyond conventional ones have been utilized, including waste substrates from various sectors of the food industry. The BC by-product can be enhanced also by adding some additives into the fermentation medium such as xanthan, agar, glycerol, ethanol, sodium alginate, carboxymethyl cellulose (CMC), etc [26]. The study that was conducted by Agustin & Padmawijaya (2018), [21] the implementation of glycerol as carbon sources into the fermentation media causes the BC films formed was thicker. In 1996, Matsuoka *et al*. (1996), [27] added lactate into the media and has increased the bacterial cellulose production compared to the control (without lactate media). In 1998, Naritami *et al*. (1998), [28] also added lactate to improve bacterial cellulose production under continuous fermentation. In the same year, they initiated a study using ethanol in bacterial cellulose production in the same operation mode [28]. Both lactate and ethanol improved bacterial cellulose production and productivity. It has been reported that water-soluble polysaccharides favoured bacterial cellulose production. Chao *et al*. (2001), [29] added agar and xanthan to the culture medium and this successfully increased bacterial cellulose production in an airlift reactor. However, they discovered that dextran usage was not effective as it inhibited *Gluconacetobacter xylinus* growth and thus decreased the bacterial cellulose production. According to Li *et al*. [15], it has been demonstrated that ethanol can serve as an energy source for ATP production during the manufacturing of BC. Hence, the additional of ethanol in fermentation media improved the production of bacterial cellulose itself. Other water-soluble polysaccharide such as acetan was studied by Ishida *et al*. (2002), [30] and they concluded that acetan favoured bacterial cellulose production by increasing the viscosity of the culture medium, which may hinder the coagulation of bacterial cellulose and cells in the media, thus accelerating the *Gluconacetobacter xylinus* BPR2001 growth. This eventually enhanced the bacterial cellulose production. Furthermore, the utilization of acetan is not practical because of economy reasons. To increase BC production and clarify the role of acetan, Bae and colleagues in 2004 introduced agar to a jar fermenter [31]. Acetic acid and ethanol were used as additives in 2018 [21] in their investigation on *Acetobacter xylinum*'s generation of bacterial cellulose. In order to limit bacterial cellulose development and improve its mechanical qualities, ethanol and acetic acid were added into the fermentation media. During the study, they found that bacterial cellulose produced by the addition of acetic acid can lead into a better characteristics and mechanical properties compared to the ethanol as additives. The enhancement of BC production increased in the presence of CMC [32]. Ten years later in year 2019, the study was conducted again by adding CMC in fermentation media and it was proved that the production rate of BC increased [33]. There are some studies that reporting the addition of water-soluble polymers into the fermentation media such as agar, xanthan, polyacrylamide-co-acylic acid (PCA) and acetan can enhance the viscosity of the broth in order to decrease the shear stress to stimulate BC to form uniform smaller pellets [34]. As shown in Table 1, various kinds of additives have been utilized in bacterial cellulose production. By adding lignosulfonate, which contains antioxidant and polyphenolic components, to the medium, the formation of gluconic acid was reduced and bacterial cellulose was raised [35]. Most of the studies improved bacterial cellulose production, favoured by the addition and the supplementation of additives.

Table 1 Additives in bacterial cellulose production

Additives	References
Lactate	Matsuoka *et al.*, 1996; Naritomi *et al.*, 1998a
Alcohols	Naritomi *et al.*, 1998b; Park *et al.*, 2003; Son *et al.*, 2003; Lu *et al.*, 2011; Santos *et al.*, 2013; Rani & Appaiah, 2013; Ko *et al.*, 2015
Agar	Bae & Shoda, 2004; Bae *et al.*, 2004; Chao *et al.*, 2001; Shah *et al.*, 2010; Atwa *et al.*, 2015
Acetan	Ishida *et al.*, 2003.
Polyacrylamide acid	Joseph *et al.*, 2003; Zhang *et al.*, 2011
Lignosulfonate	Keshk, 2006; Keshk and Sameshima, 2006a; Keshk and Sameshima, 2006b; Tsouko *et al.*, 2015
Sodium Alginate	Zhou *et al.*, 2007; Lin *et al.*, 2014; Atwa *et al.*, 2015; Shao *et al.*, 2015
Carboxymethyl cellulose (CMC)	Yamamoto & Horn, 1994; Yamamoto *et al.*, 1996; Hirai *et al.*, 1998; Seifert *et al.*, 2004; Yudianti & Indrarti, 2008; Chen *et al.*, 2009; Cheng, 2009; Grande *et al.*, 2009; Cheng *et al.*, 2011; Kose *et al.*, 2013; Ma *et al.*, 2014; Lin, 2016; Wang et al., 2016; Dayal & Catchmark, 2016
Hydroxypropylmethyl cellulose	Huang *et al.*, 2010; Ruka *et al.*, 2013.
Tween 80	Huang *et al.*, 2010; Ruka *et al.*, 2013
Poly-3-hydroxybutyrate	Barud *et al.*, 2013; Ruka *et al.*, 2013; Ruka *et al.*, 2014
Vitamin C (ascorbic acid)	Keshk, 2014.
Xylan	Weimer *et al.*, 2000
Xyloglucan	Yamamoto & Horn, 1994; Whitney *et al.*, 1995; Yamamoto *et al.*, 1996
Acetyl glucomannan	Tokoh *et al.*, 1998
Microcrystalline cellulose	Cheng *et al.*, 2009
Hyaluronic Acid	Lopes *et al.*, 2014
Cellulase	Wang *et al.*, 2016
Pectin	Dayal & Catchmark, 2016
Gelatin	Dayal & Catchmark, 2016
Cornstarch	Dayal & Catchmark, 2016
Corn steep liquor	Dayal & Catchmark, 2016
Cellulase	Wang *et al.*, 2016
Aromatic compound (conniferyl aldehyde, ferulic acid, vanilin, 4-hydroxybenzoic acid)	Zhang *et al.*, 2014
Acetic acid	Agustin & Padmawijaya, 2018
Whey	Kolesovs & Semjonovs, 2020

3.1 Effect of Agars

Bae *et al.* (2004), [31] proposed that the BC production increased when agar was implemented into the fermentation broth. The viscosity of the broth was also maintained higher from the start of cultivation due to the addition of agar. Based on study conducted by Shah *et al*. (2010), [36] agar increased the viscocity of the medium which lead into the higher yield and productivity of BC. In addition, agar was added into the jar-fermenter to prevent coagulation and clumping. Hence, the BC yield also can be enhanced [14].

3.2 Effect of Acetic Acid

A study conducted by Li *et al*. (2012), [15] proved that low concentrations of acetic acid (up to 0.2 vol% and 1 vol%) increase the BC production by *Gluconacetobacter xylinus*. However, at high concentrations of acetic acid, Li and cowokers reported that BC production was lowered due to the general toxicity of aliphatic acids. Furthermore, acetic acid can also improve BC production at certain level. A previous study was conducted on BC production by strain *Komagateibacter medellinensis* using Hestrin-Schramm (HS) altered medium by adding ethanol and acetic acid (both 0.1%) which shows an increasing in BC yield up to 279% [8].

3.3 Effect of Whey

According to Kolesovs and Semjonovs [11], whey has a high sugar content, making it suitable for use in the industrial manufacturing of a variety of biotechnology products. Whey protein is a waste that comes from the dairy industry and it contains the aforementioned compounds such as β-lactoglobulin, α-lactalbumin and bovine serum albumin in different ratios, relying on the methods of cheese manufacture [46] Whey was also known as a problematic among agriculture and industry by-products due to its impact on environment, high volumes and a few available options for effective valorisation. Whey is a by-product of the manufacture of cheese or curd that consists of large quantity of nutritionally rich component [22]. Whey was obtained from cow's milk, as well as sheep or goat and also camel's milk [45].

There is a previous study that was conducted in 2020 using *Gluconobacter sucrofermentants* B-11267 strain to observe whey as a substrate to produce BC, and the result shown that the yield produce is higher when compared to standard Hestrin-Schramm (HS) medium [11].

3.4 Effect of Sodium Alginate

Alginate is an innate anionic polysaccharide withdraw commonly from brown algae and abundant of bacteria [40]. It was reported that the BC/Alginate (Alg) nanocomposites were highly homogenous and formed a gelatinous structure with a more closed network [41]. In the same study, it was proven that the mechanical strength of BC/Alg nanocomposite in dry state was lower but relatively higher in elongation break. This indicates the flexibility. The addition of sodium alginate can alter the cellulose morphology from clumps and fibrous masses that entangled in the internals which increasing the cellulose yield [34]. Two years later, Cheng *et al*. (2009), [32] reported that sodium alginate can enhance the BC production in the agitated fermentation. Jiang and colleagues demonstrated that, as compared to pure BC alone, sodium alginate/BC has larger porosity and changes the ultrastructure of the BC [37].

3.5 Effect of Carboxymethylcellulose (CMC)

An anionic linear polymer makes up CMC, one of the cellulose derivatives that is insoluble in water. It has many uses, including those in the food industry, pharmaceutical industry, cosmetic industry, detergent industry, ceramic industry, and textile industry [42]. It was because of its distinctive characteristics, which included excellent hydrophilicity, high biocompatibility, good gas barrier properties, and a stable internal network structure [43].

The negatively charged water-soluble cellulose derivative, CMC, was mentioned by Cheng *et al*. as one technique to increase BC yield [32]. Included within the static culture was CMC. It has been demonstrated that adding CMC to the fermentation medium increases the formation of BC and influences the degree to which BC itself polymerizes. From 73 to 96% (w/w) of percent by weight, the water content of CMC-modified BC pellicle increases. According to de Lima *et al*. [44], CMC can be added to the BC culture medium, altering its viscosity and affecting the BC qualities overall as well as production rates. Previous investigations have shown that CMC has an impact on how BC structures form. The current has revealed CMC can lead to a denser formation of BC structure, thus reducing the mechanical strength and crystallinity. There is no latest evidence that shows the effect of CMC on BC properties.

3.6 Effect of Lignosulfonate

A by-product of pulping wood with acid and sulfite, lignosulfonate offers exceptional qualities like strong dispersive and sticky capabilities. As a result, it has a wide range of uses, including those of an adhesive, cement dispersion, oil well drilling agent, and soil stabiliser [38]. A study conducted by Keshk and Sameshima stated that supplementing the water-soluble polysaccharides such as lignosulfonate into the fermentation medium can enhance BC production. This is due to the evidence that shows lignosulfonate can hinder the formation of large clumps of BC. They also reported the lignosulfonate reduce the sheer stress and increase the viscosity to produce BC pellet. In 2006, Keshk conducted a study in the presence of 1% lignosulfonate using four strains of *Gluconacetobacter xylinus*. BC productivity of these four strains increase with high crystallinity index due to the presence of lignosulfonate [35]

3.7 Effect of Hydroxypropylmethyl Cellulose (HPMC)

Hydroxypropylmethyl cellulose is a water-soluble polysaccharide that is used as emulsifier [25]. A study conducted by Ruka and cowokers (2013) proposed that the inclusion of other polymers such as hydroxypropylmethyl cellulose (HPMC) into the growth media affect the mechanical features of BC. BC's mechanical characteristics. For instance, the degree of polymerization, the size of the pores, the widths of the fibres, crystallinity, and mechanical strength. Also, it was demonstrated that the inclusion of HPMC led to slightly thinner fibrils. The HPMC fibrils also seemed to be thicker, hence the difference in fibrils was not statistically significant.

3.8 Effect of Xylan and Hyaluronic Acid

It has been stated in the study conducted by Santos and coworkers [39] cellulosic surfaces are irreversibly absorbed by xylans when they contact with cellulose. In the same study, they proved that the BC itself are more crystalline than the materials with xylan [39]. They concluded that incorporating xylans on BC might alter its properties, thus increasing the roughness and the burst index. Xylans are intricate polysaccharides which are found in the walls of plant cells, particularly in hardwood and agricultural by-products. The advantages of these properties are substantial; they have high water-holding capacity, film-forming ability, and biodegradability.

Surprisingly, chemically altering xylans can produce entirely new polymers with beneficial properties. For instance, additional functional groups can be added to xylans, such as carboxyl, amino, and hydroxyl groups, which may be employed in subsequent processes. The solubility, rheological characteristics, and thermal stability of xylans can all be enhanced by these alterations.

Moreover, xylans can be chemically altered to create novel polymers with intriguing features including hydrogels, films, and nanoparticles. These materials may find use in a variety of industries, including biomedicine, food, and agriculture, which meet the demand of the BC industrial sector. As a result, xylans can be chemically modified to create new polymers with enhanced properties and possible applications [47].

Lopes and colleagues [48] proposed that hyaluronic acid (HA) supplemented to the fermentation medium can be preserved inside the BC membrane during its secretion by the bacteria. The freshly generated BC fibrils free hydroxyl groups will point towards the HA, which becomes trapped within the BC matrix. This will decrease the availability of hydroxyl groups to occupy the material surface. The BC material's surface hydrophilicity is consequently reduced. The wound healing process would benefit from this circumstance. As comparison to the BC that was left alone, the addition of HA increased the BC's Young's modulus and tensile strength. As reported by Jia *et al*. [49], the addition of HA strengthened the hydrogen bonds, resulting from the interaction between HA and BC. An approach by Wang and colleagues [50] has been attempted by preparing a BC based composite containing HA and also silk sericin. They successfully improved water holding capability and mechanical properties, while maintaining the biocompatibility of BC.

4.0 CONCLUSION

BC has been studied extensively and *Komagateibacter xylinus* (formerly known as *Gluconacetobacter xylinus*) has become the most efficient cellulose producer among the researchers. However, low yield and marketable properties have become major challenges in this field. Hence, researchers have conducted several strategies such as applying low-cost substrates and additives to reduce production cost and enhance bacterial cellulose yield. Investigating alternative media and additives is a crucial subject for the economically efficient manufacturing of BC. The amount and excellence of the BC produced would also improve with the identification of the optimal nutritional needs and growth circumstances, resulting in even more diverse applications.. Strong network and barrier features are also present, smooth texture and a gelatinous consistency, making it an excellent candidate for applications in food packaging. BC is a wonderful option for other environmental applications as it is a sustainable, biodegradable, and green bio-based substance. Implementing additives into the fermentation media can help to improve the properties of BC. This is aligned with the future directions of BC in some potential applications such as wound healing material and drug delivery.

5.0 FUTURE PROSPECTS

To enhance the sustainability of bacterial cellulose (BC) production is to use alternative and renewable feedstocks, such as lignocellulosic biomass, agricultural wastes, or food waste. This strategy reduces dependency on costly carbon sources by employing cheap, plentiful resources, increasing the economic viability and environmental friendliness of large-scale BC production. Additionally, addition of certain additives that might be toxic and have the potential to change BC's biocompatibility and structural properties should be considered. To keep BC functional and sustainable, additives must be carefully considered and chosen. Future research should evaluate cutting-edge technology like modified strains and compare the economic viability between renewable feedstocks and synthetic additions. Optimization and maximization of BC requires a balance between cost, scalability, and sustainability.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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