

## A review: Current trends and future perspectives of bacterial nanocellulose-based wound dressings

Item Type	Journal article
Authors	Pasaribu, Khatarina Meldawati;Mahendra, I. Putu;Karina, Myrtha;Masruchin, Nanang;Sholeha, Novia Amalia;Gea, Saharman;Gupta, Abhishek;Johnston, Brian;Radecka, Iza
Citation	Pasaribu, K M, Mahendra, I P, Karina, M, Masruchin, N. et al (2024) A review: Current trends and future perspectives of bacterial nanocellulose-based wound dressings, International Journal of Biological Macromolecules, 279 (4), article number 135602
DOI	<a href="https://doi.org/10.1016/j.ijbiomac.2024.135602">10.1016/j.ijbiomac.2024.135602</a>
Publisher	Elsevier BV
Journal	International Journal of Biological Macromolecules
Download date	2026-04-18 07:15:43
License	<a href="https://creativecommons.org/licenses/by-nc-nd/4.0/">https://creativecommons.org/licenses/by-nc-nd/4.0/</a>
Link to Item	<a href="https://wlv.openrepository.com/handle/2436/625926">https://wlv.openrepository.com/handle/2436/625926</a>

# A Review: Current Trends and Future Perspectives of Bacterial Nanocellulose-based Wound Dressings

Khatarina Meldawati Pasaribu<sup>1,2,3,4\*</sup>, I Putu Mahendra<sup>5</sup>, Myrtha Karina<sup>1,2,3</sup>, Nanang Masruchin<sup>1,2,3</sup>, Novia Amalia Sholeha<sup>6</sup>, Saharman Gea<sup>4,7</sup>, Abhishek Gupta<sup>8,9</sup>, Brian Johnston<sup>10</sup>, Izabela Radecka<sup>8,10</sup>

<sup>1</sup>Research Center for Biomass and Bioproducts, National Research and Innovation Agency of Indonesia (BRIN), Cibinong 16911, Indonesia.

<sup>2</sup>Research Collaboration Center for Biomass and Biorefinery, Padjajaran Science and Technopark, Jl. Ir. Soekarno, Km.21, Jatinangor 45363, Indonesia.

<sup>3</sup>Research Collaboration Center for Nanocellulose, BRIN - UNAND, Padang 25163, Indonesia

<sup>4</sup>Cellulosic and Functional Materials Research Centre, Universitas Sumatera Utara, Jl. Bioteknologi No.1, Medan 20155, Indonesia.

<sup>5</sup>Program Studi Kimia, Jurusan Sains, Institut Teknologi Sumatera, Jalan Terusan Ryacudu, Way Hui, Jati Agung, Lampung Selatan, 35365, Indonesia

<sup>6</sup>College of Vocational Studies, Bogor Agricultural University (IPB University), Jalan Kumbang No. 14, Bogor 16151, Indonesia.

<sup>7</sup>Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Sumatera Utara, Jl. Bioteknologi No. 1, Medan, 20155, Indonesia.

<sup>8</sup>Research Institute in Healthcare Science, Faculty of Science and Engineering, University of Wolverhampton, Wulfruna Street, Wolverhampton, WV1 1LY, UK; a.gupta@wlv.ac.uk (A.G.)

<sup>9</sup>School of Pharmacy, Faculty of Science and Engineering, University of Wolverhampton, Wulfruna Street, Wolverhampton, WV1 1LY, UK

<sup>10</sup>Wolverhampton School of Sciences, Faculty of Science and Engineering, University of Wolverhampton, Wulfruna Street, Wolverhampton, WV1 1LY, UK

\*corresponding author: khat004@brin.go.id

## Abstract

Bacterial cellulose (BC) has gained significant attention as a base material for wound dressings due to its superior physical properties, biocompatibility, and non-toxicity. However, to produce wound dressings that actively facilitate wound healing, BC modification is essential. To provide a comprehensive analysis of the potential research developments and the trends in bacterial cellulose-based wound dressings (BCWD), this review focuses on the BCWD research conducted in the last decade. The review highlights the optimization of BC usage as a base material for active wound dressing, including the incorporation of miscellaneous materials and the enhancement of BC properties such as ultra-transparency, anti-leakage, stretchability/flexibility, adhesiveness, conductivity, injectability, pattern, and pH-sensor ability.

**Keywords:** Bacterial Cellulose; Wound Dressing; Additional Material

## 1. INTRODUCTION

The skin provides an effective physical barrier and non-specific defense. Being in direct contact with the external environment, it is one of the most vulnerable organs to injuries and traumas, such as mechanical injuries, burns, radiation, and pathological ulcers (Shpichka et al., 2019; Zhou et al., 2022). People have been using passive wound dressings as wound healing treatments for millennia. These dressings primarily aim to shield the wound from common pathogenic microbes

47 like *Staphylococcus aureus*, *Candida albicans*, or *Pseudomonas aeruginosa*, but they often fall  
48 short in promoting the healing process (Negut et al., 2018). Specific treatment is necessary for  
49 various chronic wound types, including full-thickness wounds, and injuries with a depth of more  
50 than 4 cm, which do not heal even with the support of antibacterial dressings (Zhou et al., 2022).  
51 Additionally, burn wounds that produce more exudate require more than just antibacterial  
52 dressings. These wounds require wound dressings that are capable of providing a soothing effect  
53 and absorbing exudate (Granick et al., 2014). Therefore, continuous efforts are underway to  
54 provide wound dressings that optimally support the wound healing process.

55 Bacterial cellulose (BC) is produced by *Komagataeibacter xylinus* and it has gained a lot of  
56 attention as a potential biomaterial for wound dressing provision. It has a very fine three-  
57 dimensional structure, excellent gas permeability, high wet strength, high water content, suitable  
58 biocompatibility, and absorption capacity; all of these properties make BC a viable material that  
59 is suitable for optimization for use as a wound dressing (Mardawati et al., 2023; Portela et al.,  
60 2019). The nanofiber network structure of BC is advantageous since has good water absorption  
61 greatly helps to remove exudate, and a satisfactory moisture transmission rate can maintain an  
62 optimum moist micro-environment, conducive to granulation growth (Zywicka et al., 2018). The  
63 dressing removal process of BC based wound dressings (BCWD) is easy, painless, and does not  
64 damage the wound tissue (Dydak et al., 2021; Zhou et al., 2022). However, pure BC does not have  
65 any inherent antimicrobial properties, thus neat BC cannot be used to treat chronic non-healing  
66 wounds (Zhou et al., 2022). This review discusses this adjuvant material and healing agents that  
67 have been used with BCWD, and it also identifies research gaps that could be the focus of future  
68 research projects.

69

## 70 **2. WOUND DRESSING**

### 71 **2.1. History of wound dressing**

72 Wound care has been recorded as a widely utilized procedure since 2500 B.C. (Forrest, 1982). In  
73 ancient Mesopotamia, wound management techniques involved first cleaning the wound site with  
74 water or milk and then applying clay tablets filled with honey or resin. During 1600 B.C., patients  
75 were treated using wound dressings made of linen strips soaked in oil or fat and firmly attached to  
76 a plaster (Daunton et al., 2012). Between 460-370 B.C., in ancient Greece, the act of bandaging

77 became widespread. In addition, sterilized wool was sometimes used as an extra precaution after  
78 being treated with hot water or wine (Dhivya et al., 2015). In 1891, gauze and cotton swabs were  
79 employed as absorbent materials for the control of wound exudate. Prior to the mid-1900s, there  
80 was a prevailing belief that wounds that were dry and open would heal faster than ones that were  
81 closed. Dry wounds impede the activity of proteinase, chemotactic factors, and growth factors,  
82 which ultimately leads to a prolonged healing process for the wound (Dhivya et al., 2015; Tan &  
83 Dosan, 2019). During the mid-1980s, advanced wound dressings capable of absorbing wound fluid  
84 and maintaining wound moisture were introduced. The dressings were formulated using  
85 polyurethane foams, hydrocolloids, and gels that contained iodine. During the mid-1990s, there  
86 was an increase in the availability of wound dressings, with the development of several types such  
87 as alginates, silver/collagen, silicone mesh, hydrogel, hydrocolloids, synthetic foams, adhesive  
88 films, and tissue adhesives. In the late 20th century, the manufacturing of occlusive wound  
89 dressings that could safeguard and create a moist environment for wounds commenced (Dhivya et  
90 al., 2015). One particular dressing, BC, was initially employed in the early 1980s. BC dressing has  
91 been found to outperform standard dressings in terms of pain relief and speeding up the healing  
92 process (Ahmed et al., 2020; Islam et al., 2021).

## 93 **2.2. Passive to active wound dressing**

94 Wound dressings can be categorized as passive and active or ideal dressings. Wound dressings are  
95 classified as passive if they only function as a protective barrier and wound barrier from external  
96 environmental contaminants without facilitating the wound healing process. On the other hand,  
97 active wound dressings can facilitate the wound healing process properly. Traditional dressings,  
98 such as gauze and cotton, which are widely used for wound healing are classified as passive wound  
99 dressings. Typically dry, these dressings can adhere to the wound surface, which may result in  
100 discomfort and additional trauma during the dressing-changing process (Sarabahi, 2012). In  
101 general, wound dressing materials are classified as active or ideal based on their ability to, a) cover  
102 the wound, in order to minimize the possibility of direct interaction with the external environment  
103 that can create the risk of new trauma and protect the wound from contaminants; b) absorb wound  
104 exudate, the ideal dressing should remove excessive exudate to avoid tissue maceration; c) provide  
105 or maintain a humid environment; d) maintain appropriate tissue temperature to increase blood  
106 flow to the wound bed and promote epidermal migration; e) allows gas exchange between injured

107 tissue and the environment; f) antibacterial, enhances therapeutic action through antimicrobial,  
108 antifungal, and antiseptic activities; g) does not adhere to the wound surface and is easily removed  
109 after healing; h) contain drugs or active compounds that play a role in accelerating the wound  
110 healing process, bioactive compounds that can be delivered, such as essential oils, antibiotics, and  
111 natural antioxidants, stimulate the interaction of the dressing with the wound microenvironment  
112 and i) must be sterile, non-allergenic and non-toxic (Ciecholewska-Juśko et al., 2022; Das et al.,  
113 2022; de Amorim et al., 2022; Deng et al., 2022; Ebadati et al., 2022; Kotcharat et al., 2022; Z.  
114 Yang et al., 2022; S. Zhang et al., 2022; Zhou et al., 2022). Ongoing research is focused on  
115 developing an ideal wound dressing, not only to accelerate the wound healing process but also to  
116 ensure that patients can carry out normal activities during this time. The properties of the promoted  
117 pads include stretchability/flexibility, injectability, adhesion, patterns, ultra-transparency, and pH  
118 sensing. Further discussion of these characteristics is provided in detail in the challenge and  
119 outlook section of this article, as the literature study conducted over the last 10 years on BC-based  
120 research for this purpose remains limited. This presents an opportunity for the development of  
121 BCWD research and for new research to emerge that can fill this gap.

122

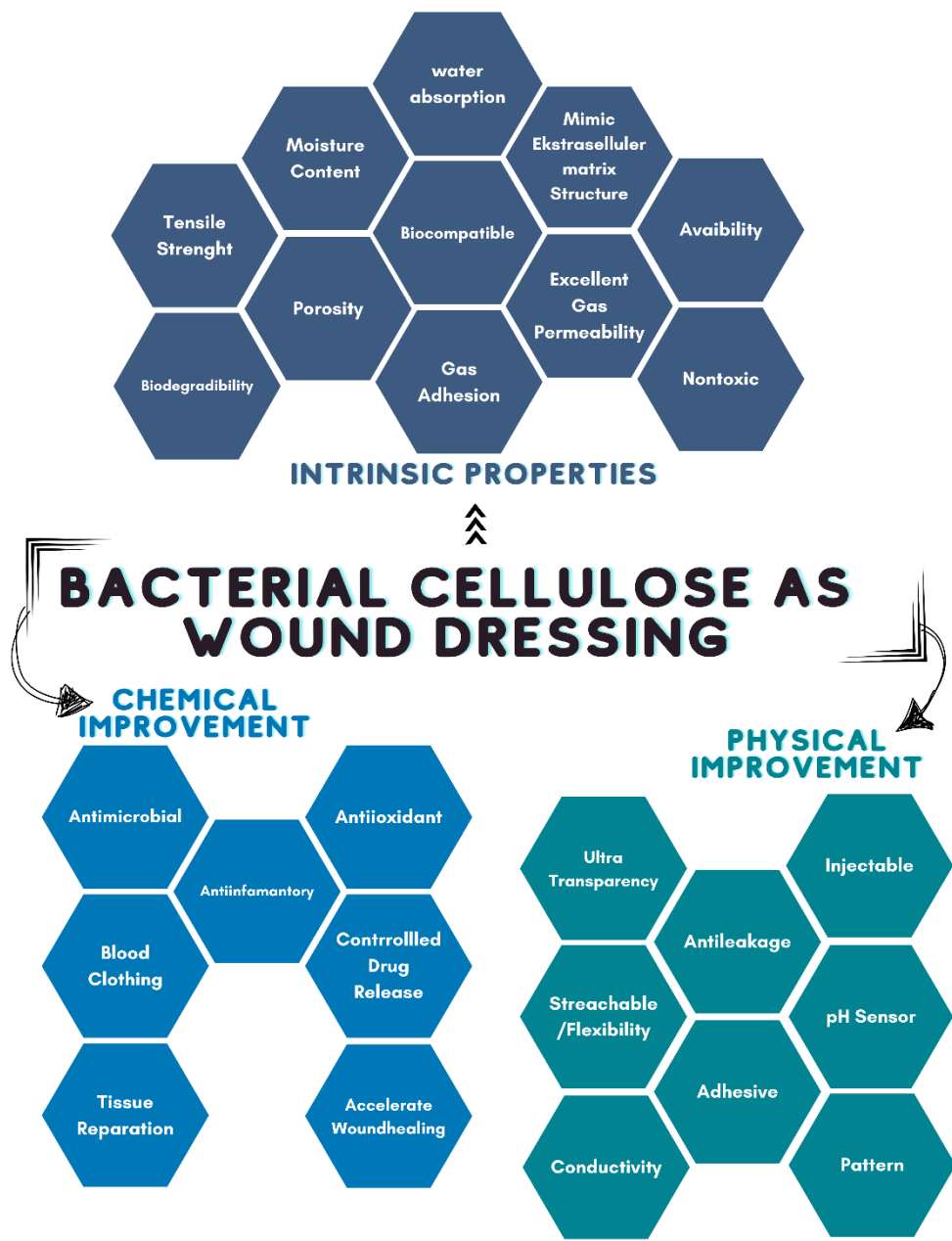
### 123 **3. BACTERIAL CELLULOSE BASED WOUND DRESSING (BCWD)**

124 BC consists of a three-dimensional network of nano-sized fibers with a diameter of 40–60 nm and  
125 a high surface area of 100–200 m<sup>2</sup>/g. BC has emerged as a highly promising material for wound  
126 dressing due to its exceptional properties and proven effectiveness. BC exhibits remarkable  
127 mechanical properties even in a never-drying condition, which ensures its stability and durability  
128 when applied to wounds. Studies have demonstrated that BC possesses high tensile strength and  
129 flexibility, allowing it to conform to various wound shapes and contours without compromising  
130 its structural integrity (Gallegos et al., 2016). Furthermore, BC exhibits high purity, as it is  
131 produced through the controlled fermentation process of specific bacteria strains. This ensures that  
132 BC dressings are free from impurities and contaminants that could hinder wound healing or cause  
133 adverse reactions (Ul-Islam et al., 2015). BC also exhibits high polymerization, indicating a dense  
134 and interconnected structure (Gea et al., 2018, 2022; Gea, Marpongahtun, et al., 2023) . This  
135 feature contributes to its ability to retain moisture, which is crucial for creating an optimal wound  
136 healing environment. The high water content of BC dressings helps maintain a moist wound  
137 environment, which has been shown to promote faster and more effective healing (Orlando & Roy,

138 2019). Moreover, BC demonstrates high crystallinity, resulting in a dense and highly organized  
139 structure. This characteristic enhances its mechanical strength, providing stability and protection  
140 to the wound site (C. Chen et al., 2022). Multiple studies have explored the efficacy of BC  
141 dressings in promoting wound healing (Gea, Putra, et al., 2023; Hasibuan et al., 2021; Pasaribu et  
142 al., 2020, 2023). Clinical trials have reported positive outcomes, including accelerated wound  
143 closure, reduced infection rates, and improved overall healing outcomes (Petersen & Gatenholm,  
144 2011). The unique properties of BC contribute to its effectiveness as a wound dressing material,  
145 making it a valuable option in modern wound management.

146  
147 BC based biomaterials possess not only negligible biocompatibility, but also adjustable chemical,  
148 physical, and mechanical properties. Various types of wound dressings have been developed from  
149 cellulose-based biomaterials and they show promising results. Bacterial cellulose-based hydrogels  
150 are an attractive material for wound dressing applications because of their high water absorption  
151 capacity and their water retention can support wound cleansing and exudate absorption process.  
152 These hydrogels also possess the ability to maintain wound proper-moisture balance, which is  
153 beneficial to facilitate a warm wound climate, to facilitate the optimal wound healing process  
154 (Mohamad et al., 2014; Walker et al., 2003). Furthermore, the flexible BC hydrogel can conform  
155 easily to the contours of the wound and maximize surface contact, forming a tight barrier between  
156 the wound and the environment. This makes BC fibers an effective barrier against contaminants,  
157 while the 3D network of nanofibers and BC porosity can facilitate cellular respiration (Ahmed et  
158 al., 2020). In addition, the BC nanofibers have a similar structure to collagen nanofibers in the  
159 extracellular matrix (ECM), making them an ideal material for facilitating tissue growth (Ahmed  
160 et al., 2020; Deng et al., 2022). Its suitability as a wound dressing, especially for burns and ulcers,  
161 has been demonstrated in several studies (Horue et al., 2023; Moradpoor et al., 2022; Sulaeva et  
162 al., 2020). Some commercially available BC based-wound dressings for topical application which  
163 are available in the market are Dermafill™, Bionext®, Bioprocess®, and XCell® (Osorio et al.,  
164 2017). However, BC itself does not have antimicrobial activity and this limitation can be overcome  
165 by developing a hybrid material, combining BC with other materials which possess antimicrobial  
166 and anti-inflammatory properties. The unique structural properties of BC make its fiber is very  
167 supportive impregnation template for additional materials that can strengthen the BC properties as  
168 a wound dressing, as illustrated in **Figure 1**. (Gupta et al., 2019, 2020). Materials that have been

169 studied as additives that can optimize the role of BC as wound dressing and its function in the  
170 wound healing process will be discussed more fully in the next section.



171  
172  
173  
174  
175

**Figure 1.** Bacterial cellulose (BC) properties as wound dressing.

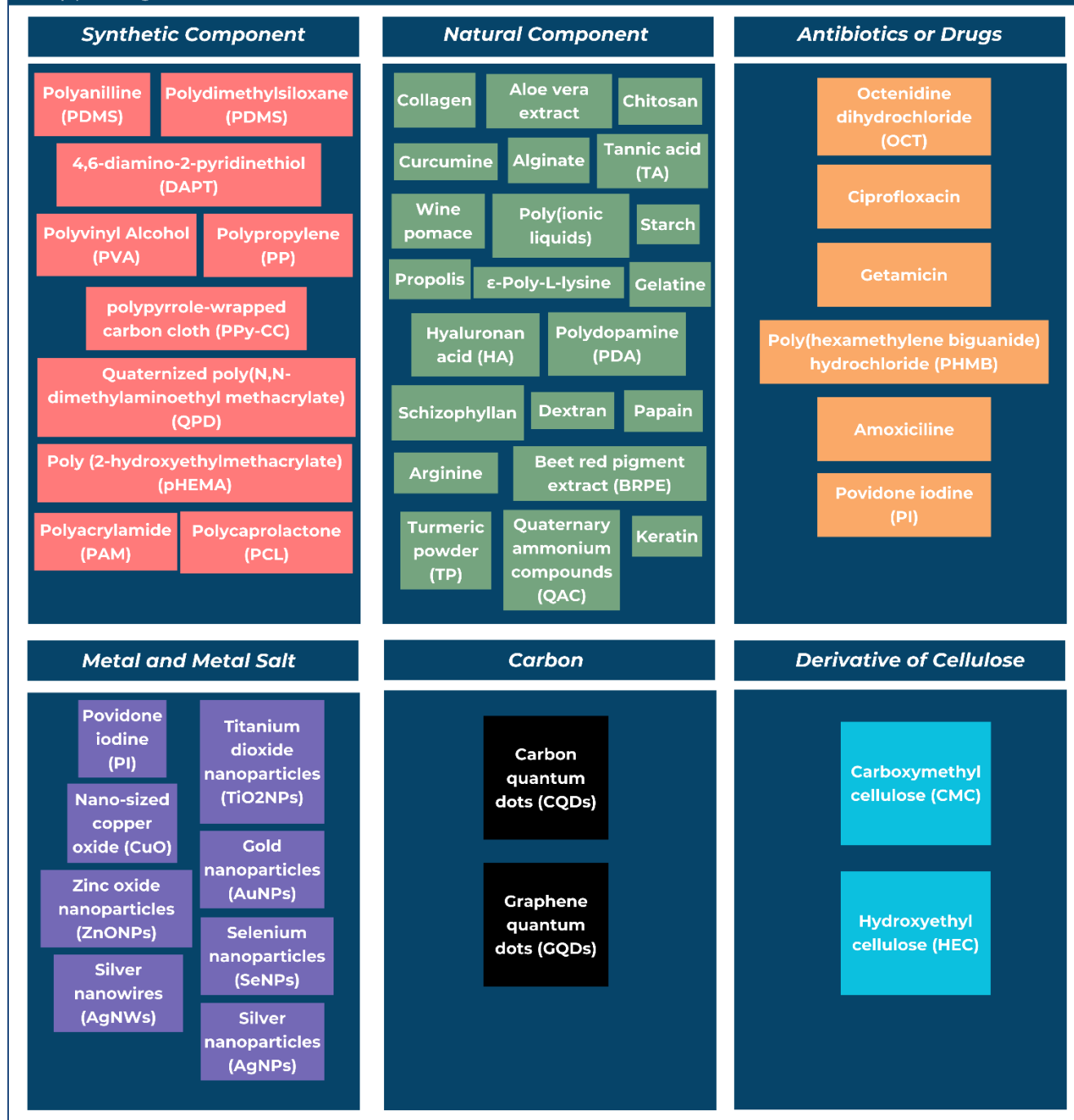
176

#### 177 **4. SUPPORTING MATERIALS IN BCWD**

178 As shown in **Figure 2**, different types of antimicrobial and healing agents are often added to make  
179 BC-based wound dressing (BCWD). These include carbon, metal or salt metal nanoparticles, and  
180 natural organic compounds from plants like curcumin, chitosan, amino acids, or alkalis. Also  
181 included are synthetic components, antiseptics, or antibiotic materials. The application of wound  
182 dressings with anti-microbial properties significantly accelerated wound closure by eradicating  
183 biofilms that hindered the healing process. **Table 1** displays the detailed properties of various BC-  
184 based wound dressings enriched with other materials, and this section will discuss the properties  
185 of some of the added materials.

# BACTERIAL CELLULOSE BASED WOUND DRESSING

## Supporting Materials



186  
187  
188

**Figure 2.** Supporting material that was used in BCWD research article in 10 years.

## 189 **4.1. Synthetic component**

### 190 **4.1.1. Polyvinyl alcohol**

191 The utilization of polyvinyl alcohol (PVA), bacterial cellulose (BC), and their composites in  
192 various biomedical applications has garnered significant attention. These applications include the  
193 development of scaffolds for tissue engineering, articular cartilage, heart valves, and artificial  
194 corneas (Busuioc et al., 2023; Millon & Wan, 2006; Wahid et al., 2020). One prominent area where  
195 PVA/BC composites have shown great potential is in wound management. *In vitro* studies have  
196 demonstrated that PVA/BC composite dressings exhibit excellent antimicrobial properties,  
197 promoting wound healing and preventing infections (Song et al., 2021). Moreover, *in vivo*, studies  
198 utilizing animal models have revealed that PVA/BC composite dressings exhibit enhanced wound  
199 closure rates, reduced inflammation, and improved tissue regeneration compared to neat PVA or  
200 BC alone (Avcioglu, 2022). These findings highlight the potential of PVA/BC composites as  
201 advanced wound dressings for clinical applications. However, despite the promising results, there  
202 are still some weaknesses and areas for future improvement. One limitation is the need for further  
203 optimization of the composite fabrication process, including the selection of suitable crosslinking  
204 methods and techniques to enhance mechanical properties and stability (Yi et al., 2023).  
205 Additionally, long-term studies assessing the biodegradability and biocompatibility of PVA/BC  
206 composites in the context of wound healing are necessary to ensure their safety and efficacy. Future  
207 work should focus on conducting more comprehensive *in vivo* studies, including larger animal  
208 models and clinical trials, to validate the effectiveness of PVA/BC composites in real-world wound  
209 management scenarios. Moreover, investigating the release kinetics of bioactive agents  
210 incorporated into the composite matrix could offer opportunities for controlled drug delivery,  
211 enhancing the therapeutic properties of PVA/BC composite dressings (Busuioc et al., 2023).  
212 Furthermore, exploring the potential of PVA/BC composites for other biomedical applications  
213 beyond wound management, such as tissue engineering scaffolds or drug delivery systems, holds  
214 great promise and warrants further investigation. In summary, PVA/BC composites demonstrate  
215 immense potential for wound management applications. Previous studies have shown their  
216 efficacy in promoting wound healing and preventing infections. However, further optimization,  
217 long-term biocompatibility assessment, and larger-scale studies are necessary to advance the  
218 understanding and utilization of PVA/BC composites in wound management and other biomedical  
219 applications.

220

#### 221 **4.1.2. Polycaprolactone**

222 Polycaprolactone (PCL) is a biocompatible and biodegradable synthetic polyester known for its  
223 mechanical strength and versatility. It has found applications as a ceramics substitute material in  
224 biomedicine (Kim et al., 2022; Siddiqui et al., 2021; X. Yang et al., 2021). However, the use of  
225 PCL in wound management is limited by challenges such as poor cell adhesion and the use of  
226 volatile solvents during preparation (X. Yang et al., 2021; S. Zhang et al., 2019). To address these  
227 limitations, researchers have explored the use of PCL/bacterial cellulose (BC) composites for  
228 wound management. BC, with its high water-holding capacity and biocompatibility, serves as an  
229 ideal matrix for incorporating PCL to create flexible wound dressings (Aydogdu et al., 2018;  
230 Kotcharat et al., 2021). The combination of PCL and BC in the composite harnesses the mechanical  
231 strength of PCL and the beneficial characteristics of BC, making it a promising material for wound  
232 management applications. Previous studies have investigated the potential of PCL/BC composites  
233 for wound healing. *In vitro* studies have demonstrated enhanced cell adhesion and proliferation on  
234 PCL/BC composite scaffolds, indicating their ability to support tissue regeneration (Aydogdu et  
235 al., 2018). *In vivo* studies utilizing animal models have shown improved wound closure rates,  
236 reduced inflammation, and enhanced tissue regeneration when compared to neat PCL or BC alone  
237 (Mohaghegh et al., 2023). These findings highlight the potential of PCL/BC composites as  
238 advanced wound dressings for clinical applications. Despite these promising results, there are still  
239 some weaknesses that need to be addressed. One limitation is the need for further optimization of  
240 the composite fabrication process to enhance mechanical properties and stability (Kotcharat et al.,  
241 2021). Additionally, long-term studies are required to assess the biodegradability and long-term  
242 biocompatibility of PCL/BC composites in wound healing scenarios. Future work should focus on  
243 conducting more comprehensive *in vivo* studies using larger animal models to validate the  
244 effectiveness and safety of PCL/BC composites in real-world wound management. Further  
245 investigation is also needed to understand the release kinetics of bioactive agents incorporated into  
246 the composite matrix for controlled drug delivery purposes, thus enhancing the therapeutic  
247 properties of PCL/BC composite dressings (Das et al., 2022). Moreover, exploring the potential of  
248 PCL/BC composites for other biomedical applications beyond wound management, such as tissue  
249 engineering scaffolds or drug delivery systems, should be pursued. In summary, the use of PCL/BC  
250 composites in wound management shows promise due to their enhanced properties and

251 biocompatibility. Previous studies have demonstrated their potential for promoting wound healing  
252 and tissue regeneration. However, further optimization, long-term biocompatibility evaluation,  
253 and larger-scale studies are necessary to advance the understanding and utilization of PCL/BC  
254 composites in wound management and other biomedical applications.

255

## 256 **4.2.Natural component**

### 257 **4.2.1. Chitosan**

258 Chitosan, a linear cationic polysaccharide derived from chitin found in crustacean exoskeletons,  
259 possesses inherent biocompatibility, biodegradability, and hemostatic properties (Kumari et al.,  
260 2017; Matica et al., 2019; Mozalewska et al., 2017). It also exhibits antimicrobial, antioxidant, and  
261 wound healing attributes, making it a prime candidate for wound dressing applications (Behera et  
262 al., 2017; S. H. Chen et al., 2013; Matica et al., 2019). Clinical studies have confirmed the efficacy  
263 of chitosan in accelerating wound healing compared to dressings devoid of chitosan (Koehler et  
264 al., 2018). This wound healing potential is attributed to chitosan's ability to promote cell  
265 proliferation, collagen synthesis, and hyaluronic acid formation (Koehler et al., 2018). Chitosan  
266 can be processed into various forms, including membranes, sponges, scaffolds, and hydrogels.  
267 Among these, hydrogels are particularly advantageous due to their ability to protect the wound,  
268 interact with the wound bed, facilitate wound contraction, and maintain an optimal moist healing  
269 environment (T. Wang et al., 2012). However, a limitation of chitosan is its susceptibility to  
270 deformation under stress (S. H. Chen et al., 2013). To address this, researchers have explored  
271 combining chitosan with other polymers to enhance its mechanical properties. In this context,  
272 bacterial nanocellulose (BC) has emerged as a promising candidate. The hydroxyl groups on the  
273 BC surface can be readily oxidized into aldehyde groups, enabling covalent crosslinking with  
274 chitosan. This crosslinking not only improves the mechanical strength of the resulting hydrogel  
275 but also creates a structure that closely mimics the extracellular matrix, promoting cell viability  
276 and cell proliferation (Deng et al., 2022). Furthermore, integrating BC with chitosan in hydrogel  
277 formulations introduces additional benefits, such as improved moisture management and  
278 breathability, which are crucial for maintaining an optimal moist wound healing environment  
279 (Stanescu et al., 2021). This composite material demonstrates the potential for various  
280 applications, including self-healing wound dressings and transdermal patches capable of  
281 controlled drug delivery (Khamrai et al., 2017).

282

283 **4.2.2. Starch**

284 Starch, a readily available natural polysaccharide composed primarily of amylose and  
285 amylopectin, offers promising applications for wound dressings material due to its affordability,  
286 biocompatibility, and biodegradability (T. Jiang et al., 2020; Pal et al., 2006). However, its high  
287 water affinity and weak mechanical strength limit its effectiveness (T. Jiang et al., 2020). These  
288 shortcomings can be overcome by combining starch with other polymers to create composite  
289 hydrogels or chemically modifying them (T. Jiang et al., 2020; Pal et al., 2006) (Naseri-Nosar &  
290 Ziora, 2018). Oxidized starch and hydroxyethyl starch are examples of such modifications used in  
291 wound dressing production (Hadisi et al., 2018; Kamoun, 2016) (Lee et al., 2012). Previous studies  
292 have shown that incorporating starch and collagen into BC yields wound dressings with desirable  
293 properties, including good moisture content, tensile strength (TS), and water solubility (WS). The  
294 increased WS is likely attributed to the abundance of hydroxyl groups in the polar polymeric  
295 matrices, promoting the formation of soluble materials that enhance biodegradability.  
296 Additionally, these studies demonstrated that the transparency of the resulting wound dressings  
297 allows for continuous wound monitoring without disturbing the injured area, potentially reducing  
298 the risk of secondary infections, particularly in dermal lesions (Nunes et al., 2021).

299

300 **4.2.3. Alginate**

301 Alginate, a naturally occurring polysaccharide derived from marine brown algae and certain  
302 bacteria, has garnered significant attention in biomedicine, particularly in the field of wound  
303 management, owing to its hydrophilic, biocompatible, and non-toxic properties (Catanzano et al.,  
304 2015; Kondaveeti et al., 2018; Malagurski et al., 2018; Rezvanian et al., 2017). Alginate's ability  
305 to promote cell migration, angiogenesis, and collagen I production has led to its incorporation into  
306 commercially available hydrogel dressings, such as Purilon® Gel and Nu-Gel™ Hydrogel  
307 (Koehler et al., 2018). In the context of wound dressings, BC has emerged as a promising material  
308 due to its unique properties. However, BC's relatively short drying time presents a challenge in its  
309 application (Sulaeva et al., 2020). To address this limitation, composite fabrication with alginate  
310 has been explored as a potential solution. The incorporation of alginate into the BC matrix has  
311 been shown to enhance water absorption capacity, thereby extending the dressing's functional  
312 lifespan and potentially reducing the frequency of dressing changes required (Chiaoprakobkij et

313 al., 2011; Sulaeva et al., 2020). Furthermore, this composite structure has demonstrated the  
314 capacity to accommodate the incorporation of additional components, such as antimicrobial  
315 agents. Previous research has indicated that the modification of BC with alginate represents a  
316 promising avenue for the large-scale production of novel wound dressing materials with optimized  
317 properties. This approach not only addresses the drying time limitation of BC but also opens up  
318 possibilities for the development of multifunctional dressings that can promote wound healing  
319 while simultaneously preventing infection (Sulaeva et al., 2020).

320

### 321 **4.3. Metal and Metal salt**

322 Since ancient times, the Greeks, Egyptians, and Romans have used the antimicrobial properties of  
323 various metals and certain salts to clean wounds. Recently, research exploiting the antibacterial  
324 properties of metals has developed in the form of nanoparticles (Pormohammad et al., 2021). Metal  
325 nanoparticles are reported to be more effective at inhibiting the growth of pathogenic bacteria  
326 because of their interaction ability, which can produce lethal reactive oxygen species (ROS) and  
327 disrupt the membrane integrity of bacterial respiration processes (Wahid et al., 2014). BC  
328 composite films reinforced with several metal nanoparticles have been reported to exhibit  
329 antibacterial properties and be biocompatible during *in vitro* studies (Ullah et al., 2016).

330

#### 331 **4.3.1. Silver nanoparticles**

332 Silver nanoparticles (AgNPs) are metal nanoparticles that are usually synthesized from the  
333 reduction of silver nitrate (AgNO<sub>3</sub>) solution with strong reducing agents, such as sodium  
334 borohydride. AgNPs possess high specific surface areas that have demonstrated excellent  
335 cytotoxicity against the development of colonies of fungi, viruses, and Gram-positive (*S. aureus*)  
336 and Gram-negative (*E. coli* and *P. aeruginosa*) bacteria, which are frequently encountered in  
337 infected wounds (Gupta et al., 2016). In wound dressing applications, emerging BC has no  
338 antibacterial activity and is not able to hinder wound infections. AgNPs has used to modify the  
339 antibacterial properties of BC (Moniri et al., 2018). A previous study confirmed that  
340 AgNPs/CUR:HP $\beta$ CD loaded in BC produce hydrogels with broad-spectrum antimicrobial activity  
341 along with antioxidant properties. These hydrogels demonstrated broad-spectrum antimicrobial  
342 activity along with antioxidant properties (Gupta et al., 2020). Moreover, the AgNPs have a  
343 tendency to aggregate, which leads to the loss of special features related to the nanoscale

344 dimension. Thus, BC can act as a template for the nucleation and growth of in situ synthesized  
345 nanoparticles in the BC/AgNPs composite (Jalili Tabaii & Emtiazi, 2018; Moniri et al., 2018).

346

### 347 **4.3.2. Zinc oxide nanoparticles**

348 Zinc oxide nanoparticles (ZnONPs) are non-toxic, biocompatible, antibacterial, and can accelerate  
349 wound healing (J. Jiang et al., 2018). In BC-based nanocomposites, it was observed that the  
350 nanoparticles managed to penetrate and enter the BC matrix. The wound dressing properties  
351 produced from this composite are very flexible so that they can be applied to wounds on active  
352 body parts or uneven skin surfaces. BC-ZnO nanocomposites are also reported to successfully  
353 inhibit the growth of pathogenic bacteria and accelerate the wound healing process and remarkable  
354 tissue regeneration (Khalid et al., 2017).

355

## 356 **4.4. Antibiotics or Drugs**

### 357 **4.4.1. Octenidine dihydrochloride**

358 Octenidine dihydrochloride (OCT) is an antiseptic that is particularly suitable for wound care due  
359 to its antifungal, antibacterial, and partially antiviral properties with a wide pH range (Koburger et  
360 al., 2010). In addition, OCT can clear bacterial biofilms in patients with chronic wounds (Cutting  
361 & Westgate, 2012). Furthermore, OCT did not alter skin cell architecture morphologically or  
362 increase apoptosis when applied to human skin. The application of OCT is also reported to be  
363 successful in minimizing scars on wounds resulting from surgical procedures (Seiser et al., 2021).  
364 BC dressings modified with antimicrobial agents, such as OCT, will provide a prolonged release  
365 and high fluid-holding capacity (Ciecholewska-Juško et al., 2022).

366

### 367 **4.4.2. Gentamicin**

368 Gentamicin, an aminoglycoside antibiotic with established clinical applications in the treatment of  
369 bone and soft tissue infections, has been extensively studied in conjunction with collagen-based  
370 drug delivery systems (Michalska-Sionkowska et al., 2018). Notably, gentamicin works well  
371 against both first- and second-degree bacterial skin and wound infections, especially those caused  
372 by gram-negative strains (Anjum et al., 2018; Lukáč et al., 2019). To address the inherent lack of  
373 antibacterial activity in bacterial cellulose (BC), a promising wound dressing material, researchers  
374 have explored the incorporation of antimicrobial agents. Researchers have integrated gentamicin,

375 among other antibiotics or antiseptics, into BC matrices to enhance wound closure by eradicating  
376 biofilm. In a previous study, researchers impregnated polycaprolactone (PCL) into BC to fabricate  
377 flexible bacterial cellulose-based PCL membranes (BCP), then functionalized these membranes  
378 with antibiotics to create composite scaffolds for infectious wound healing. These scaffolds  
379 exhibited excellent antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus*,  
380 with a release profile characterized by an initial burst release followed by controlled release over  
381 48 hours (Das et al., 2022).

382

## 383 **4.5. Carbon**

### 384 **4.5.1. Carbon quantum dots**

385 Carbon Quantum Dots (CQDs), typically smaller than 10 nm, exhibit notable antibacterial activity  
386 against both Gram-positive bacteria (e.g., *Staphylococcus aureus*) and Gram-negative bacteria  
387 (e.g., *Escherichia coli*) (Malmir et al., 2020). Additionally, CQDs are recognized for their non-  
388 toxic and biocompatible properties. Within the medical field, CQDs find extensive use in drug  
389 delivery and various therapeutic applications (Singh et al., 2018). *In vivo*, *in vitro*, and *in ovo*  
390 models have demonstrated CQDs' ability to facilitate the healing process. Notably, the utilization  
391 of quantum dots (QDs) in wound healing can expedite tissue reconstruction and wound closure  
392 (Salleh & Fauzi, 2021). Prior research has led to the fabrication of a bacterial cellulose (BC)/CQD-  
393 titanium dioxide (TiO<sub>2</sub>) composite as an active injectable dressing to accelerate wound healing.  
394 The incorporation of CQD-TiO<sub>2</sub> nanoparticles (NPs) has been shown to enhance the mechanical  
395 strength and antibacterial properties of BC. These CQD-TiO<sub>2</sub> NPs have demonstrated antibacterial  
396 properties, and their integration into the bacterial cellulose matrix presents a promising avenue for  
397 developing advanced wound healing dressing (Malmir et al., 2020).

398

### 399 **4.5.2. Graphene quantum dots**

400 Graphene quantum dots (GQDs) are a derivative of the graphene family, and they consist of very  
401 small graphite fragments, less than 10 nm in size. GQDs with different properties can be set up  
402 with different strategies. GQD is reported to have photodynamic characteristics. The combination  
403 of photodynamic agents and antibiotics is a good choice for antibacterial treatment, which can  
404 overcome antibiotic resistance (N. Wang et al., 2020). Compared to graphene oxide (GO), GQD  
405 has been proven to be less hazardous and to be non-toxic. As a result, GQD has received a lot of

406 attention in the fields of materials science and biological applications. Significant advances have  
407 been made in the biomedical field, particularly concerning the use of GQDs in cellular imaging,  
408 drug delivery, and biosensors. Therefore, the use of GQDs in wound dressings is highly suitable  
409 for *in vivo* wound disinfection (H. Sun et al., 2014). Previous study mentioned that introducing  
410 GQDs into the BC matrix conspicuously improved the growth inhibition of Gram-negative and  
411 Gram-positive bacteria (Ebadati et al., 2022).

412

## 413 **4.6. Derivative of cellulose**

### 414 **4.6.1. Carboxymethylcellulose**

415 Carboxymethyl cellulose (CMC), a cellulose derivative, is frequently utilized in the  
416 pharmaceutical industry as an emulsifier, stabilizer, lubricant, and viscosity modifier in the  
417 formulation of various medicinal dosage forms (Hebeish et al., 2013). CMC, a semi-natural  
418 polymer, exhibits excellent water absorption and swelling properties. Furthermore, CMC is  
419 physiologically non-toxic and demonstrates compatibility with mucous membranes, bones, and  
420 skin (Cielecka et al., 2019), making it suitable for wound and skin healing applications. A key  
421 advantage of CMC is its ability to form films and blend with other biocompatible, less toxic, and  
422 hydrophilic polymers (Basu et al., 2018). In the fabrication of wound dressings with bacterial  
423 cellulose (BC), CMC has been supplemented into the culture media to modify the structural  
424 properties of BC. This supplementation delays the aggregation of cellulose molecules, resulting in  
425 BC/CMC membranes with flexible properties and high absorption capacity for artificial exudate  
426 (Cielecka et al., 2019).

427

### 428 **4.6.2. Hydroxyethylcellulose**

429 Hydroxyethyl cellulose (HEC) is a semi-synthetic polymer, one of the most important  
430 commercially soluble cellulose derivatives. HEC is formed by the etherification of cellulose base  
431 cells with chlorohydrin or ethylene oxide when the hydroxyl group of the cellulose molecule of  
432 the compound is substituted with a hydroxyethyl group (Tudoroiu et al., 2021). Due to its high  
433 biocompatibility with low toxicity and non-immunogenicity, HEC is widely used in many  
434 pharmaceutical, cosmetic, biotechnology, and industrial applications as stabilizers, thickeners, or  
435 coatings (El Fawal et al., 2018). The polysaccharide structure of HEC makes this hydrophilic  
436 biopolymer have the capacity to absorb and hold large amounts of water, or high wound exudates.

437 The elastic strength of the structure allows HEC to be able to experience an expansion of the  
 438 molecular dimensions without modification of the structural stability in the form of a gel. HEC  
 439 also presents adequate biocompatibility, biodegradability, insignificant toxicity, genetics, and  
 440 cementing properties (Tudoroiu et al., 2021). Similar to CMC, HEC was incorporated via in situ  
 441 BC fabrication in order to modify the crystal size, crystallinity, porosity, and water holding  
 442 capacity of the BC in BC/HEC membrane thus optimizing its potential utility as wound dressings  
 443 (Cielecka et al., 2019).

444

445

**Table 1.** BCWD compounds and their properties.

<b>Compounds</b>	<b>WD Properties</b>	<b>References</b>
BC/AgNP	Antimicrobial activity	(Berndt et al., 2013)
DABC/Chitosan	High self-healing effectiveness and strong antibacterial activity	(Deng et al., 2022)
BC/Papain	Antimicrobial activity	(Asanarong et al., 2021)
BCWs/ PHEMA/AgNPs	Excellent antibacterial activity, great transparency, and flexible	(Di et al., 2017)
BC/SPG/ZnONPs	Antibacterial, biocompatible, and promotes the fibroblast cell proliferation	(Hamedi & Shojaosadati, 2021)
MOBC/Arg	Promoted proliferation, migration, and expression of Collagen-I of fibroblasts and endothelial cells	(Qiao et al., 2018)
BC/CMC/ $\epsilon$ -PL	Good cytocompatibility and antimicrobial activities	(Fürsatz et al., 2018)
p-BC/PDMS/PANI	3-D chronic wound pH sensor with flexibility properties	(M. Yang & Choy, 2021)
BCM/ZnO	Excellent antibacterial activity	(Luo et al., 2020)
BC/HA	Does not need to add extra and expensive HA during production	(Liu & Catchmark, 2020)
BCa/chitosan/curcumin	Antimicrobial and wound healing capability	(Khamrai et al., 2017)
BC/SA–AgSD	Excellent antibacterial activities and good biocompatibility	(Shao et al., 2015)
BC-Au-DAPT	Treating superbug-infected wounds.	(Li et al., 2017)

BC-ZnONPs	Treating burn wounds	(Khalid et al., 2017)
BC-octenidine dihydrochloride (OCT)	Highly-exuding, biofilm infected chronic wounds.	(Ciecholewska-Juško et al., 2022)
BC/PCL-GEN and BC/PCL-SM	Excellent antimicrobial activity and drug control release	(Das et al., 2022)
BC/CUR/ GQDs	High-antimicrobial activity and cell viability	(Ebadati et al., 2022)
BC/AgNPs	Broad-spectrum antimicrobial activity along with antioxidant properties	(Gupta et al., 2020)
BC/TA/Mg	Excellent inhibitory activities on biofilms and eligible cytotoxicity grade	(W. He et al., 2021)
BC/PVA	Prolonged antibiotic release	(Hamed & Shojaosadati, 2021)
BC/Keratin	Protection and support activities for the cells involved in detersion and regeneration	(Radu et al., 2021)
BC/CQD-TiO 2	Antibacterial wound dressing	(Malmir et al., 2020)
BC/PIL	Good biocompatibility and high antimicrobial activity	(X. He et al., 2020)
BC/ [EDA][DLA-Tyr]	Biocompatibility and antimicrobial activity	(Zywicka et al., 2018)
BC/AgNPs	Excellent antibacterial activities and healing properties	(Moniri et al., 2018)
BC/Chi	Significant growth inhibition against target bacteria	(Savitskaya et al., 2017)
BC/AgZ	Antimicrobial activity	(Gupta et al., 2016)
BC/PI/PHMB	Controlled drug delivery	(Wiegand et al., 2015)
BC/CoI-I/Chi	Antimicrobial activity	(Pasaribu et al., 2020)
BC/CUR:HPβCD	Exhibited hemocompatibility, cytocompatibility, anti-staphylococcal and antioxidant abilities	(Gupta et al., 2019)
sPVA/BC	Bioactive 3D-Shaped for treatment of hand lesions	(Osorio et al., 2017)
BC (rGO)/Ag-pDA	Excellent antimicrobial and biocompatibility	(L. Zhang et al., 2021)
BC/CMC	Enhanced flexibility and liquid sorption capacity	(Cielecka et al., 2019)
BC/HEC		

BC/Col-I/HACC	Favorable anti-infective properties and to promote healing ability for infected wounds	(Zhou et al., 2022)
BC/Propolis	Antimicrobial activity	(Hodel et al., 2022)
BC/PCL/Aloe vera extract	Excellent swelling behavior and kinetic release rate, low cell viability	(Ebadati et al., 2022)
BC/Starch/Collagen	Transparent biocomposites	(Nunes et al., 2021)
BC/PCL	Thermal decomposition behavior was stable up to 400 °C	(Kotcharat et al., 2021)
BC/Chitosan	Good biocompatibility for human dermal fibroblast viability and proliferation	(Stanescu et al., 2021)
BC/Col-1/AgNWs	Slow down the release of silver ions, but also endow dressing excellent cytocompatibility	(Z. Yang et al., 2022)
BC/PP-Fe@HCMS/Gox	Remarkable biocompatibility, hemostat, and bacteria deactivation ability both <i>in vitro</i> and <i>in vivo</i>	(Ebadati et al., 2022)
BC/Alginate@PHMB	Smooth dressing exchange, good antimicrobial activity for highly colonized wounds	(Sulaeva et al., 2020)
BC/Chi/Cip	Antimicrobial activity and lack of cytotoxicity in human fibroblasts	(Cacicedo et al., 2020)
BC/keratin	<i>In vitro</i> , culturing of the mats with L929 fibroblast cells determined the biocompatibility of the fibrous composite along with improved cell adhesion and proliferation.	(Azarniya et al., 2019)
BC/AgNPs	Strong antibacterial activity and good biocompatibility	(Jalili Tabaii & Emtiazi, 2018)
BC/AgNPs	Superior antimicrobial activity	(Adepu & Khandelwal, 2018)
BC/Col-I	Promoted statistically significant differences in tissue repair	(De Sousa Moraes et al., 2016)
p-BC/AgNP	More firmly with fibers after the carbonization process, and no rapid release of Ag <sup>+</sup> .	(Yan et al., 2015)

QPD/BC	Antibacterial and anti-cell adhesion properties	(Ou et al., 2024)
S-g-BC/BRPE	Could monitor the wound state via pH sensor ability	(T. Chen et al., 2024)
CuO/PDA/BC	Advantageous air permeability, superior mechanical properties, high hydrophilicity, and strong antibacterial activities.	(Han et al., 2024)
BC/TP	Accelerated wound healing, hair growth, and tissue regeneration.	(Khan et al., 2024)
BC/PDA/CuS	Accelerate the full-thickness wound closure	(M. Sun et al., 2024)
PPy-CC/BC	Sustained sterilization using biosafe low-voltage electrical fields and facilitated antibacterial capabilities via physically-stimulated treatment.	

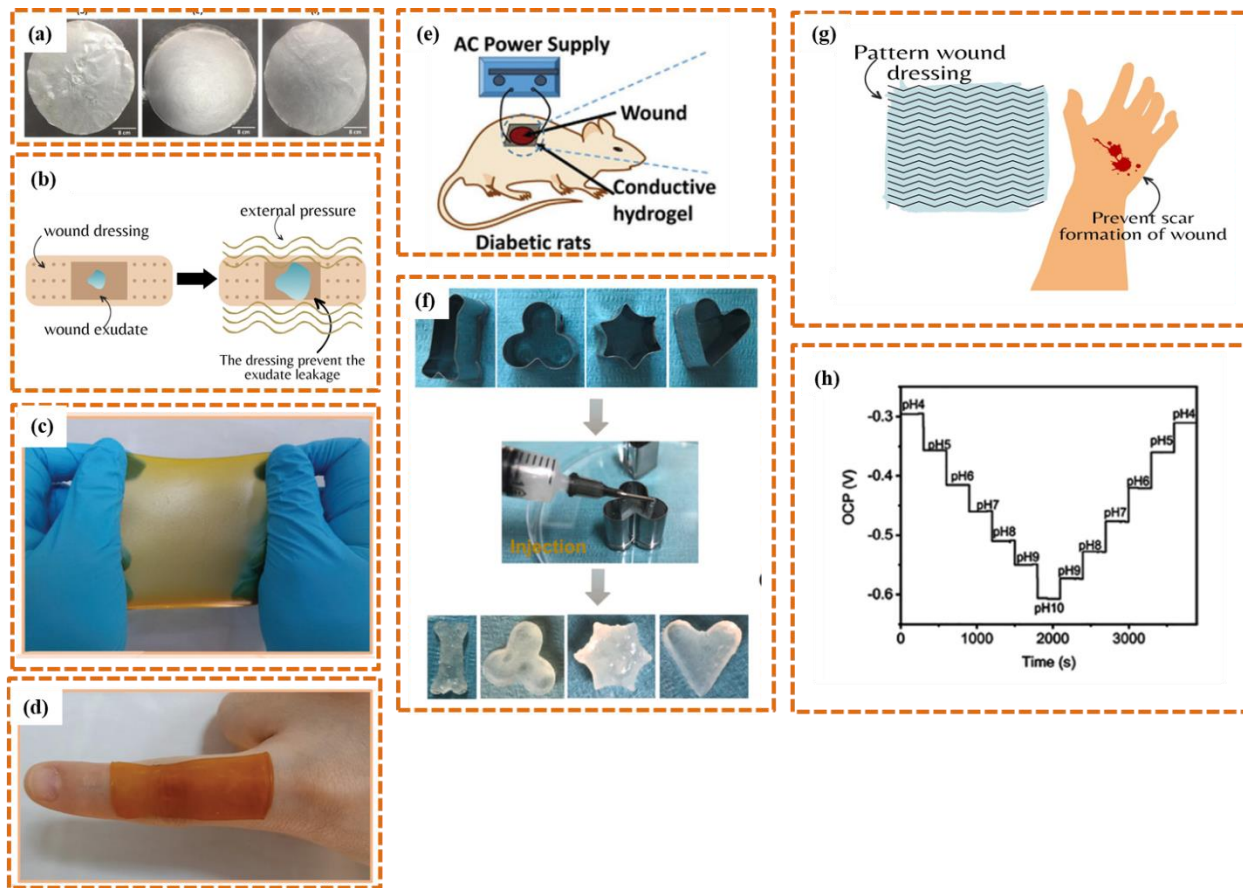
446 \*Gold nanoparticles (Au-NPs); 4,6-diamino-2-pyrimidinethiol (DAPT); Zinc oxide nanoparticles  
447 (ZnONPs); dialdehyde modified bacterial cellulose (DABC); polycaprolactone (PCL); gentamicin (GEN);  
448 streptomycin (SM); hydroxypropyltrimethyl ammonium chloride chitosan (HACC); collagen I (Col-I);  
449 silver nanowires (AgNWs); graphene quantum dots (GQDs); hollow mesoporous nanocatalyst  
450 (Fe@HCMS); glucose oxidase (GOx); silver nanoparticles (AgNPs); Tannic Acid (TA); Magnesium (Mg);  
451 pyrolyzed BC (p-BC); polydimethyl-siloxane (PDMS); polyaniline (PANI); poly(hexamethylene  
452 biguanide) hydrochloride (PHMB); Carbon Quantum Dots (CQD); Titanium dioxide (TiO<sub>2</sub>); Poly(ionic  
453 liquids) (PIL); Chitosan (Chi); ciprofloxacin (Cip); Hyaluronic acid (HA); carboxyl BC (BCM);  
454 carboxymethyl cellulose (CMC); hydroxyethyl cellulose (HEC); ethylene diamine (EDA); dilinoleic acid  
455 (DLA); tyrosine (Tyr); microporous oxidized BC (MOBC); Arginine (Arg); ε-Poly-L-lysine (ε-PL); BC  
456 whiskers (BCWs); poly (2-hydroxyethyl methacrylate) (PHEMA); anionic BC (BCa); silver zeolites (AgZ);  
457 povidone-iodine (PI) and polihexanide (PHMB); BC/AgNP after carbonization (p-BC/AgNP);  
458 curcumin:hydroxypropyl-β-cyclodextrin (CUR:HPβCD); quaternized poly(*N,N*-dimethylaminoethyl  
459 methacrylate) (QPD); silane grafted BC (S-g-BC); beet red pigment extract (BRPE); nano-sized  
460 copper oxide (CuO); turmeric powder (TP); copper sulfide nanoparticles (CuS); polypyrrole-  
461 wrapped carbon cloth (PPy-CC)

462

## 463 5. CHALLENGE AND OUTLOOK

464 The gradual development of wound healing theory has led to the rapid advancement of wound  
465 dressing provision, with a focus on modifying dressings to play an active role in the wound healing  
466 process. At present, wound dressings are expected to do more than just act as a cover for the  
467 damaged area, possess antibacterial activity, and support the healing process. The development of

468 BCWD innovations, including the addition and combination of other materials, is necessary to  
 469 create wound dressings that allow patients to continue their normal lives while receiving wound  
 470 care. In this section, we will discuss physical modifications that have not yet been widely  
 471 developed in BCWD, their respective advantages, and the urgency for the development of wound  
 472 dressings, as illustrated in **Figure 3**.



473  
 474  
 475 **Figure 3.** Illustrated of wound dressing modification (a) Ultra transparency (Nunes et al., 2021)  
 476 (This article is an open access article distributed under the terms and conditions of the Creative  
 477 Commons Attribution (CC BY) license); (b) anti-leakage (Santamaria & Amit, 2021), (c)  
 478 stretchability/flexibility (Z. Yang et al., 2021), (d) adhesiveness (Z. Yang et al., 2021), (e)  
 479 conductivity (Lu et al., 2019), (f) inject-ability (Deng et al., 2022), (g) pattern (Jin et al., 2018),  
 480 and (h) pH sensor- ability (M. Yang & Choy, 2021). Copyright 2021, Multidisciplinary Digital  
 481 Publishing Institute. Copyright 2021, Wounds International. Copyright 2021, Wiley. Copyright  
 482 2020, Wiley. Copyright 2022, Elsevier. Copyright 2018, Springer. Copyright 2021, Elsevier.

483

### 484 **5.1. Ultra transparency**

485 The provision of wound dressing with ultra-transparent properties needs to be done to have good  
486 wound observation. Wound dressings with poor transparency are not conducive to wound  
487 visualization and consequently to monitor the progress of wound healing, dressing changes are  
488 becoming more frequent. This process often causes skin tissue damage, resulting in pain and even  
489 secondary trauma to the wound (Nunes et al., 2021; Xia et al., 2020). It has been reported that the  
490 production of nanocellulose by *Gluconoacetobacter* bacteria using culture media results in  
491 remarkable transparency (Orlando et al., 2020).

### 493 **5.2. Anti-leakage**

494 The 'saturation' term in wound dressing provision refers to the state in which the dressing either  
495 contains a sufficient amount of exudate or has reached the maximum level of exudate absorption,  
496 filling the entire dressing structure with liquid. Thus, it is no longer able to absorb or accommodate  
497 the wound exudate (S. et al., 2018; Santamaria & Amit, 2021). It was suggested that dressing  
498 replacement should be done before the exudate reaches the edge (border) of the dressing, as the  
499 dressing can leak before it becomes saturated, especially when the bandage is subjected to  
500 unintentional compression (Caprini et al., 2012). As discussed in the previous section, the  
501 frequency of dressing changes is important to consider in the wound healing process because  
502 changing dressings too often can be inconvenient and cause secondary trauma (Berg et al., 2019).  
503 Furthermore, providing anti-leakage wound dressing materials helps the patient live as normally  
504 as possible.

### 506 **5.3. Stretchable/flexibility**

507 The lack of flexibility in adapting to the surface of injured or shaped skin is a significant obstacle  
508 for patients with wounds in areas with uneven contours or that are actively moving, such as joints,  
509 popliteal fossa, axillae, and folds of muscle. This is particularly problematic as most wound  
510 dressings available today do not possess the special features necessary to accommodate these  
511 challenges (Z. Yang et al., 2021). This limitation needs to be exceeded to ensure that patients with  
512 injuries can live normally during the healing process.

### 514 **5.4. Adhesiveness**

515 Currently, commercial dressings such as gauze, which are widely used in wound treatment,  
516 nonetheless require the use of duct tape for skin adhere. However, it is known that some people  
517 have skin allergies to masking tape (Z. Yang et al., 2021). The development of adhesive wound  
518 dressings is needed to make wound dressings that have adhesive power thus that they can stick  
519 and bind the damaged tissue, cover the wounds as a shield to avoid bacterial infection, achieve a  
520 good hemostatic effect or sealant to stop bleeding or preventing the leakage of fluid or gas from  
521 the wound (Ghobril & Grinstaff, 2015; Liang, Zhao, Hu, Han, et al., 2019). The properties that  
522 need to be considered in the development of adhesive wound dressings are being able to achieve  
523 "self-cleaning" antibacterial properties, easy to remove from wounds, not sticky or leave no residue  
524 on the skin after removal, and not causing allergies (Z. Yang et al., 2021).

525

## 526 **5.5. Conductivity**

527 Recently, the provision of biomaterial-based wound dressings with similar conductivity properties  
528 to human skin has been significantly studied, due to its effectiveness in supporting the wound  
529 healing process as the human body has an endogenous bioelectrical system in which the surface  
530 of intact human skin carries a more negative charge than the deeper layers of the skin (Korupalli  
531 et al., 2021). However, when a defect or injury occurs on the skin, the deeper epidermal and wound  
532 cells would be in positive charge. The combination of the positive charge of the wound and the  
533 negative charge of the normal skin around creates what is called as 'skin battery'. This bioelectric  
534 current facilitates wound healing best when the wound tissue is moistened (Liang, Zhao, Hu, Han,  
535 et al., 2019). In the fabrication of conductive wound dressings, the basic principle that needs to be  
536 considered is the process of combining electroactive substances such as carbon nanomaterials,  
537 conductive polymers (CPs), or metal-based materials into biomaterial polymers (Korupalli et al.,  
538 2021; Lu et al., 2019). Currently, many conductive wound dressings have been designed in various  
539 forms, such as electrospun nanofibers, membranes, films, hydrogels, cryogels, and foams (Yu et  
540 al., 2022).

541

## 542 **5.6. Injectable**

543 To effectively treat wounds, particularly those resulting from sports activities, it is necessary to  
544 develop injectable wound dressings. Such dressings can adapt to various types of laceration  
545 damage and can be applied to wounds in motion where the ability of the dressing to accommodate

546 compression and stretching activities is required (Deng et al., 2022). This type of wound dressing  
547 is usually developed in the form of a hydrogel where a dressing can be applied to cover irregularly  
548 shaped wounds and prevent the wound site from a second infection (Liang, Zhao, Hu, Chen, et al.,  
549 2019).

550

### 551 **5.7. Pattern**

552 From a histological perspective, the excessive accumulation of collagen secreted by fibroblasts,  
553 irregular arrangement of fibroblasts, and fibroblast proliferation are the primary causes of scarring.  
554 It has been suggested that cells can detect, interpret, and respond to chemical and physical  
555 information in their immediate surroundings because the extracellular matrix is composed of both  
556 nano- and micron-sized polysaccharides and protein molecules (Hynes, 2009). As a result, the  
557 physical signals in the extracellular matrix are mainly affected by the micro-nano-scale surface  
558 morphology. This interaction of cells with morphology is referred to as contact guidance, and it is  
559 known that contact guidance affects different cell properties including morphology,  
560 differentiation, migration, and adhesion (Friedl, 2004; Rørth, 2011). The pattern wound dressing  
561 is known to promote consistent dense collagen fiber organization, suppress the inflammatory  
562 response, prevent overgrowth of granulation tissue, and as a result reduce aberrant collagen  
563 deposition and scar thickness. Thus, a pattern wound dressing can be developed to prevent scar  
564 formation after burns or other injuries (Jin et al., 2018).

565

### 566 **5.8. pH sensor-ability**

567 In contrast to acute wounds, which heal in a short time, chronic wounds require extensive  
568 monitoring and therapy of bacterial infections and healing progress. In chronic wounds, pH is a  
569 key parameter in wound monitoring, because pH changes are often caused by bacterial infection.  
570 Due to the presence of alkaline byproducts produced by the bacterial proliferation process, the pH  
571 value in chronic wounds is typically greater than 7.4, whereas the pH value in normal skin is  
572 slightly acidic between 5.5 and 6.5 (Ochoa et al., 2014; Schneider et al., 2007). Currently, wound  
573 pH has only been measured at a few different sites in the injury area. However, for effectiveness,  
574 the pH measurement in chronic wounds should be done throughout the wound site using a high  
575 spatial resolution, which is, it was beyond the capacity of most commercial probes that are  
576 available today (M. Yang & Choy, 2021).

577

## 578 **6. Conclusion**

579 BC has been used as base material in wound dressings fabrication due to its outstanding physical  
580 properties, such as the 3D fiber porous structure, the ability to absorb water, and the hydrogen  
581 bonding structure, which makes BC a good template for modification and the impregnation process  
582 with other materials. However, is known that BC does not contain any substances that can prevent  
583 bacterial growth or actively support the wound healing process, which is a basic requirement for  
584 providing active wound dressings. To fulfill this goal, ongoing research is being conducted to  
585 optimize the use of BC material in wound dressings. A variety of natural, synthetic, metallic, and  
586 other materials have been utilized to optimize BC wound dressings and support the wound healing  
587 process. Many reports indicate that the combination of BC with other materials has resulted in  
588 wound dressings possessing active properties that support the wound healing process. However, a  
589 future challenge for BCWD provision is to produce wound dressings with more advanced  
590 properties. These dressings should not only accelerate the wound healing process but also reduce  
591 the risk of causing secondary trauma during dressing changes and enable patients to carry out  
592 normal activities during the healing process. These properties include stretchability/flexibility,  
593 injectability, adhesiveness, pattern, ultra-transparency, pH sensing, anti-leakage, and conductivity.

594

## 595 **7. Acknowledgment**

596 Khatarina Meldawati Pasaribu expresses her sincere gratitude to the National Research and  
597 Innovation Agency of Indonesia (BRIN) for providing the necessary resources to conduct her  
598 postdoctoral work at the Nanocellulose research group at the Research Center for Biomass and  
599 Bioproducts from July 1, 2022, to June 30, 2023.

600

## 601 **8. References**

- 602 Adepu, S., & Khandelwal, M. (2018). Broad-spectrum antimicrobial activity of bacterial  
603 cellulose silver nanocomposites with sustained release. *Journal of Materials Science*, *53*(3),  
604 1596–1609. <https://doi.org/10.1007/s10853-017-1638-9>
- 605 Ahmed, J., Gultekinoglu, M., & Edirisinghe, M. (2020). Bacterial cellulose micro-nano fibres for  
606 wound healing applications. *Biotechnology Advances*, *41*(April), 107549.  
607 <https://doi.org/10.1016/j.biotechadv.2020.107549>
- 608 Anjum, A., Sim, C. H., & Ng, S. F. (2018). Hydrogels Containing Antibiofilm and Antimicrobial  
609 Agents Beneficial for Biofilm-Associated Wound Infection: Formulation Characterizations  
610 and In vitro Study. *AAPS PharmSciTech*, *19*(3), 1219–1230.

611 <https://doi.org/10.1208/s12249-017-0937-4>

612 Asanarong, O., Minh Quan, V., Boonrungsiman, S., & Sukyai, P. (2021). Bioactive wound  
613 dressing using bacterial cellulose loaded with papain composite: Morphology,  
614 loading/release and antibacterial properties. *European Polymer Journal*, *143*(November  
615 2020), 110224. <https://doi.org/10.1016/j.eurpolymj.2020.110224>

616 Avcioglu, N. H. (2022). Bacterial cellulose: recent progress in production and industrial  
617 applications. *World Journal of Microbiology and Biotechnology*, *38*(5), 1–13.  
618 <https://doi.org/10.1007/s11274-022-03271-y>

619 Aydogdu, M. O., Altun, E., Crabbe-Mann, M., Brako, F., Koc, F., Ozen, G., Kuruca, S. E.,  
620 Edirisinghe, U., Luo, C. J., Gunduz, O., & Edirisinghe, M. (2018). Cellular interactions with  
621 bacterial cellulose: Polycaprolactone nanofibrous scaffolds produced by a portable  
622 electrohydrodynamic gun for point-of-need wound dressing. *International Wound Journal*,  
623 *15*(5), 789–797. <https://doi.org/10.1111/iwj.12929>

624 Azarniya, A., Tamjid, E., Eslahi, N., & Simchi, A. (2019). Modification of bacterial  
625 cellulose/keratin nanofibrous mats by a tragacanth gum-conjugated hydrogel for wound  
626 healing. *International Journal of Biological Macromolecules*, *134*, 280–289.  
627 <https://doi.org/10.1016/j.ijbiomac.2019.05.023>

628 Basu, P., Narendrakumar, U., Arunachalam, R., Devi, S., & Manjubala, I. (2018).  
629 Characterization and Evaluation of Carboxymethyl Cellulose-Based Films for Healing of  
630 Full-Thickness Wounds in Normal and Diabetic Rats. *ACS Omega*, *3*(10), 12622–12632.  
631 <https://doi.org/10.1021/acsomega.8b02015>

632 Behera, S. S., Das, U., Kumar, A., Bissoyi, A., & Singh, A. K. (2017). Chitosan/TiO<sub>2</sub> composite  
633 membrane improves proliferation and survival of L929 fibroblast cells: Application in  
634 wound dressing and skin regeneration. *International Journal of Biological Macromolecules*,  
635 *98*, 329–340. <https://doi.org/10.1016/j.ijbiomac.2017.02.017>

636 Berg, L., Lazaro Martinez, J. L., Serena, T. E., Dhoonmoon, L., & Ousey, K. (2019). Meeting  
637 report: Promoting wound healing by optimising dressing change frequency. *Wounds*  
638 *International*, *10*(3), 68–75.  
639 [https://singaporetech.remotexs.co/user/login?url=https://search.ebscohost.com/login.aspx?di](https://singaporetech.remotexs.co/user/login?url=https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip&db=ccm&AN=138756103&site=ehost-live&scope=site)  
640 [rect=true&AuthType=ip&db=ccm&AN=138756103&site=ehost-live&scope=site](https://singaporetech.remotexs.co/user/login?url=https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip&db=ccm&AN=138756103&site=ehost-live&scope=site)

641 Berndt, S., Wesarg, F., Wiegand, C., Kralisch, D., & Müller, F. A. (2013). Antimicrobial porous  
642 hybrids consisting of bacterial nanocellulose and silver nanoparticles. *Cellulose*, *20*(2),  
643 771–783. <https://doi.org/10.1007/s10570-013-9870-1>

644 Busuioc, C., Isopencu, G. O., & Deleanu, I. M. (2023). Bacterial Cellulose–Polyvinyl Alcohol  
645 Based Complex Composites for Controlled Drug Release. *Applied Sciences (Switzerland)*,  
646 *13*(2). <https://doi.org/10.3390/app13021015>

647 Cacicedo, M. L., Pacheco, G., Islan, G. A., Alvarez, V. A., Barud, H. S., & Castro, G. R. (2020).  
648 Chitosan-bacterial cellulose patch of ciprofloxacin for wound dressing: Preparation and  
649 characterization studies. *International Journal of Biological Macromolecules*, *147*, 1136–  
650 1145. <https://doi.org/10.1016/j.ijbiomac.2019.10.082>

651 Caprini, J. A., Partsch, H., & Simman, R. (2012). Venous ulcers. *Journal of the American*  
652 *College of Clinical Wound Specialists*, *4*(3), 54–60.  
653 <https://doi.org/10.1016/j.jccw.2013.11.001>

654 Catanzano, O., D’Esposito, V., Acierno, S., Ambrosio, M. R., De Caro, C., Avagliano, C.,  
655 Russo, P., Russo, R., Miro, A., Ungaro, F., Calignano, A., Formisano, P., & Quaglia, F.  
656 (2015). Alginate-hyaluronan composite hydrogels accelerate wound healing process.

657 *Carbohydrate Polymers*, 131, 407–414. <https://doi.org/10.1016/j.carbpol.2015.05.081>

658 Chen, C., Ding, W., Zhang, H., Zhang, L., Huang, Y., Fan, M., Yang, J., & Sun, D. (2022).  
659 Bacterial cellulose-based biomaterials: From fabrication to application. *Carbohydrate*  
660 *Polymers*, 278(December 2021), 118995. <https://doi.org/10.1016/j.carbpol.2021.118995>

661 Chen, S. H., Tsao, C. T., Chang, C. H., Lai, Y. T., Wu, M. F., Chuang, C. N., Chou, H. C.,  
662 Wang, C. K., & Hsieh, K. H. (2013). Assessment of reinforced poly(ethylene glycol)  
663 chitosan hydrogels as dressings in a mouse skin wound defect model. *Materials Science and*  
664 *Engineering C*, 33(5), 2584–2594. <https://doi.org/10.1016/j.msec.2013.02.031>

665 Chen, T., Yan, Y., Zhou, X., Liu, W., Tan, R., Wei, D., Feng, Y., Cui, Q., Wang, W., Zhang, R.,  
666 Wu, N., Xu, H., Qu, D., Zhang, H., Wu, G., & Zhao, Y. (2024). An antioxidant hydrogel  
667 dressing with wound pH indication function prepared based on silanized bacterial  
668 nanocellulose crosslinked with beet red pigment extract. *International Journal of Biological*  
669 *Macromolecules*, 269(P1), 131824. <https://doi.org/10.1016/j.ijbiomac.2024.131824>

670 Chiaoprakobkij, N., Sanchavanakit, N., Subbalekha, K., Pavasant, P., & Phisalaphong, M.  
671 (2011). Characterization and biocompatibility of bacterial cellulose/alginate composite  
672 sponges with human keratinocytes and gingival fibroblasts. *Carbohydrate Polymers*, 85(3),  
673 548–553. <https://doi.org/https://doi.org/10.1016/j.carbpol.2011.03.011>

674 Ciecholewska-Juško, D., Junka, A., & Fijałkowski, K. (2022). The cross-linked bacterial  
675 cellulose impregnated with octenidine dihydrochloride-based antiseptic as an antibacterial  
676 dressing material for highly-exuding, infected wounds. *Microbiological Research*, 263.  
677 <https://doi.org/10.1016/j.micres.2022.127125>

678 Cielecka, I., Szustak, M., Kalinowska, H., Gendaszewska-Darmach, E., Rynngajłło, M.,  
679 Maniukiewicz, W., & Bielecki, S. (2019). Glycerol-plasticized bacterial nanocellulose-  
680 based composites with enhanced flexibility and liquid sorption capacity. *Cellulose*, 26(9),  
681 5409–5426. <https://doi.org/10.1007/s10570-019-02501-1>

682 Cutting, K. F., & Westgate, S. J. (2012). The use of wound cleansing solutions in chronic  
683 wounds. *Wounds UK*, 8(4), 130–133.

684 Das, M., Zandraa, O., Mudenur, C., Saha, N., Saha, P., Mandal, B., & Katiyar, V. (2022).  
685 Composite Scaffolds Based on Bacterial Cellulose for Wound Dressing Application. *ACS*  
686 *Applied Bio Materials*, 5(8), 3722–3733. <https://doi.org/10.1021/acsabm.2c00226>

687 Daunton, C., Kothari, S., Smith, L., & Steele, D. (2012). A history of materials and practices for  
688 wound management. *Wound Practice and Research The Australian Journal of Wound*  
689 *Management*, 20(4), 174–186.  
690 <http://search.informit.com.au/documentSummary;dn=058025628512911;res=IELHEA>

691 de Amorim, J. D. P., da Silva Junior, C. J. G., de Medeiros, A. D. M., do Nascimento, H. A.,  
692 Sarubbo, M., de Medeiros, T. P. M., Costa, A. F. de S., & Sarubbo, L. A. (2022). Bacterial  
693 Cellulose as a Versatile Biomaterial for Wound Dressing Application. *Molecules*, 27(17),  
694 5580. <https://doi.org/10.3390/molecules27175580>

695 De Sousa Moraes, P. R. F., Saska, S., Barud, H., De Lima, L. R., Da Conceicao Amaro Martins,  
696 V., De Guzzi Plepis, A. M., Ribeiro, S. J. L., & Gaspar, A. M. M. (2016). Bacterial  
697 cellulose/collagen hydrogel for wound healing. *Materials Research*, 19(1), 106–116.  
698 <https://doi.org/10.1590/1980-5373-MR-2015-0249>

699 Deng, L., Wang, B., Li, W., Han, Z., Chen, S., & Wang, H. (2022). Bacterial cellulose reinforced  
700 chitosan-based hydrogel with highly efficient self-healing and enhanced antibacterial  
701 activity for wound healing. *International Journal of Biological Macromolecules*,  
702 217(April), 77–87. <https://doi.org/10.1016/j.ijbiomac.2022.07.017>

703 Dhivya, S., Vijaya, V., & Santhini, E. (2015). Review article Wound dressings – a review.  
704 *BioMedicine*, 5(4), 24–28. <https://doi.org/10.7603/s40>

705 Di, Z., Shi, Z., Ullah, M. W., Li, S., & Yang, G. (2017). A transparent wound dressing based on  
706 bacterial cellulose whisker and poly(2-hydroxyethyl methacrylate). *International Journal of*  
707 *Biological Macromolecules*, 105, 638–644. <https://doi.org/10.1016/j.ijbiomac.2017.07.075>

708 Dydak, K., Junka, A., Dydak, A., Brożyna, M., Paleczny, J., Fijalkowski, K., Kubiela, G.,  
709 Aniołek, O., & Bartoszewicz, M. (2021). In vitro efficacy of bacterial cellulose dressings  
710 chemisorbed with antiseptics against biofilm formed by pathogens isolated from chronic  
711 wounds. In *International Journal of Molecular Sciences* (Vol. 22, Issue 8).  
712 <https://doi.org/10.3390/ijms22083996>

713 Ebadati, A., Ghalandari, B., Hasanzadeh, A., & Karimi, M. (2022). Curcumin/Graphene  
714 Quantum Dot-Loaded Bacterial Nanocellulose Platform for Drug Delivery and Wound  
715 Dressing. *Nano*, 17(04), 2250021. <https://doi.org/10.1142/S1793292022500217>

716 El Fawal, G. F., Abu-Serie, M. M., Hassan, M. A., & Elnouby, M. S. (2018). Hydroxyethyl  
717 cellulose hydrogel for wound dressing: Fabrication, characterization and in vitro evaluation.  
718 *International Journal of Biological Macromolecules*, 111, 649–659.  
719 <https://doi.org/10.1016/j.ijbiomac.2018.01.040>

720 Forrest, R. D. (1982). Early history of wound treatment. *Journal of the Royal Society of*  
721 *Medicine*, 75(3), 198–205. <https://doi.org/10.1177/014107688207500310>

722 Friedl, P. (2004). Prespecification and plasticity: Shifting mechanisms of cell migration. *Current*  
723 *Opinion in Cell Biology*, 16(1), 14–23. <https://doi.org/10.1016/j.ceb.2003.11.001>

724 Fürsatz, M., Skog, M., Sivlér, P., Palm, E., Aronsson, C., Skallberg, A., Greczynski, G., Khalaf,  
725 H., Bengtsson, T., & Aili, D. (2018). Functionalization of bacterial cellulose wound  
726 dressings with the antimicrobial peptide  $\epsilon$ -poly-L-Lysine. *Biomedical Materials (Bristol)*,  
727 13(2). <https://doi.org/10.1088/1748-605X/aa9486>

728 Gallegos, A. M. A., Carrera, S. H., Parra, R., Keshavarz, T., & Iqbal, H. M. N. (2016). Bacterial  
729 Cellulose: A Sustainable Source to Develop Value-Added Products – A Review.  
730 *BioResources*, 11(2), 5641–5655. <https://doi.org/10.15376/BIORES.11.2.5641-5655>

731 Gea, S., Marpongahtun, Nasution, D. Y., Pasaribu, K. M., Amaturrahim, S. A., Piliang, A. F., &  
732 Siahaan, R. C. (2023). The characterization of agitated bacterial cellulose-based paper  
733 synthesized at various rotational speeds. *AIP Conference Proceedings*, 040021(May 2023),  
734 040021. <https://doi.org/10.1063/5.0136601>

735 Gea, S., Pasaribu, K. M., Sarumaha, A. A., & Rahayu, S. (2022). Cassava starch / bacterial  
736 cellulose-based bioplastics with *Zanthoxylum acanthopodium*. *Biodiversitas*, 23(5), 2601–  
737 2608. <https://doi.org/10.13057/biodiv/d230542>

738 Gea, S., Pasaribu, K. M., Sebayang, K., Julianti, E., Amaturrahim, S. A., Rahayu, S. U., &  
739 Hutapea, Y. A. (2018). Enhancing the quality of nata de coco starter by channeling the  
740 oxygen into the bioreactor through agitation method. *AIP Conference Proceedings*,  
741 2049(December). <https://doi.org/10.1063/1.5082469>

742 Gea, S., Putra, I. B., Lindarto, D., Pasaribu, K. M., Saraswati, Y., Karina, M., Goei, R., & Tok,  
743 A. I. Y. (2023). Bacterial cellulose impregnated with andaliman (*Zanthoxylum*  
744 *acanthopodium*) microencapsulation as diabetic wound dressing. *International Journal of*  
745 *Biological Macromolecules*, 253(P1), 126572.  
746 <https://doi.org/10.1016/j.ijbiomac.2023.126572>

747 Ghobril, C., & Grinstaff, M. W. (2015). The chemistry and engineering of polymeric hydrogel  
748 adhesives for wound closure: A tutorial. *Chemical Society Reviews*, 44(7), 1820–1835.

749 <https://doi.org/10.1039/c4cs00332b>

750 Granick, M. S., Sood, A., & Tomaselli, N. L. (2014). Wound Dressings and Comparative  
751 Effectiveness Data. *Advances in Wound Care*, 3(8), 511–529.  
752 <https://doi.org/10.1089/wound.2012.0401>

753 Gupta, A., Briffa, S. M., Swingler, S., Gibson, H., Kannappan, V., Adamus, G., Kowalczyk, M.,  
754 Martin, C., & Radecka, I. (2020). Synthesis of Silver Nanoparticles Using Curcumin-  
755 Cyclodextrins Loaded into Bacterial Cellulose-Based Hydrogels for Wound Dressing  
756 Applications. *Biomacromolecules*, 21(5), 1802–1811.  
757 <https://doi.org/10.1021/acs.biomac.9b01724>

758 Gupta, A., Keddie, D. J., Kannappan, V., Gibson, H., Khalil, I. R., Kowalczyk, M., Martin, C.,  
759 Shuai, X., & Radecka, I. (2019). Production and characterisation of bacterial cellulose  
760 hydrogels loaded with curcumin encapsulated in cyclodextrins as wound dressings.  
761 *European Polymer Journal*, 118(June), 437–450.  
762 <https://doi.org/10.1016/j.eurpolymj.2019.06.018>

763 Gupta, A., Low, W. L., Radecka, I., Britland, S. T., Mohd Amin, M. C. I., & Martin, C. (2016).  
764 Characterisation and in vitro antimicrobial activity of biosynthetic silver-loaded bacterial  
765 cellulose hydrogels. *Journal of Microencapsulation*, 33(8), 725–734.  
766 <https://doi.org/10.1080/02652048.2016.1253796>

767 Hadisi, Z., Nourmohammadi, J., & Nassiri, S. M. (2018). The antibacterial and anti-  
768 inflammatory investigation of Lawsonia Inermis-gelatin-starch nano-fibrous dressing in  
769 burn wound. *International Journal of Biological Macromolecules*, 107(2018), 2008–2019.  
770 <https://doi.org/10.1016/j.ijbiomac.2017.10.061>

771 Hamed, S., & Shojaosadati, S. A. (2021). Preparation of antibacterial ZnO NP-containing  
772 schizophyllan/bacterial cellulose nanocomposite for wound dressing. *Cellulose*, 28(14),  
773 9269–9282. <https://doi.org/10.1007/s10570-021-04119-8>

774 Han, B., Liu, F., Hu, S., Chen, X., Lin, C., Lee, I. S., & Chen, C. (2024). An antibacterial  
775 membrane based on Janus bacterial cellulose with nano-sized copper oxide through  
776 polydopamine conjugation for infectious wound healing. *Carbohydrate Polymers*,  
777 332(February), 121923. <https://doi.org/10.1016/j.carbpol.2024.121923>

778 Hasibuan, P. A. Z., Yuandani, Tanjung, M., Gea, S., Pasaribu, K. M., Harahap, M., Perangin-  
779 Angin, Y. A., Prayoga, A., & Ginting, J. G. (2021). Antimicrobial and antihemolytic  
780 properties of a CNF/AgNP-chitosan film: A potential wound dressing material. *Heliyon*,  
781 7(10), e08197. <https://doi.org/10.1016/j.heliyon.2021.e08197>

782 He, W., Zhang, Z., Chen, J., Zheng, Y., Xie, Y., Liu, W., Wu, J., & Mosselhy, D. A. (2021).  
783 Evaluation of the anti-biofilm activities of bacterial cellulose-Tannic acid-magnesium  
784 chloride composites using an in vitro multispecies biofilm model. *Regenerative*  
785 *Biomaterials*, 8(6), 1–17. <https://doi.org/10.1093/rb/rbab054>

786 He, X., Yang, Y., Song, H., Wang, S., Zhao, H., & Wei, D. (2020). Polyanionic Composite  
787 Membranes Based on Bacterial Cellulose and Amino Acid for Antimicrobial Application.  
788 *ACS Applied Materials and Interfaces*, 12(13), 14784–14796.  
789 <https://doi.org/10.1021/acsami.9b20733>

790 Hebeish, A., Hashem, M., El-Hady, M. M. A., & Sharaf, S. (2013). Development of CMC  
791 hydrogels loaded with silver nano-particles for medical applications. *Carbohydrate*  
792 *Polymers*, 92(1), 407–413. <https://doi.org/10.1016/j.carbpol.2012.08.094>

793 Hodel, K. V. S., Machado, B. A. S., Sacramento, G. da C., Maciel, C. A. de O., Oliveira-Junior,  
794 G. S., Matos, B. N., Gelfuso, G. M., Nunes, S. B., Barbosa, J. D. V., & Godoy, A. L. P. C.

795 (2022). Active Potential of Bacterial Cellulose-Based Wound Dressing: Analysis of Its  
796 Potential for Dermal Lesion Treatment. *Pharmaceutics*, *14*(1222).  
797 <https://doi.org/10.3390/pharmaceutics14061222>

798 Horue, M., Silva, J. M., Berti, I. R., Brandão, L. R., Barud, H. da S., & Castro, G. R. (2023).  
799 Bacterial Cellulose-Based Materials as Dressings for Wound Healing. *Pharmaceutics*,  
800 *15*(2), 1–26. <https://doi.org/10.3390/pharmaceutics15020424>

801 Hynes, R. O. (2009). Extracellular matrix: not just pretty fibrils Richard. *Science*, *326*(5957),  
802 1216–1219. <https://doi.org/10.1126/science.1176009>. Extracellular

803 Islam, S. U., Ul-Islam, M., Ahsan, H., Ahmed, M. B., Shehzad, A., Fatima, A., Sonn, J. K., &  
804 Lee, Y. S. (2021). Potential applications of bacterial cellulose and its composites for cancer  
805 treatment. *International Journal of Biological Macromolecules*, *168*, 301–309.  
806 <https://doi.org/10.1016/j.ijbiomac.2020.12.042>

807 Jalili Tabaii, M., & Emtiazi, G. (2018). Transparent nontoxic antibacterial wound dressing based  
808 on silver nano particle/bacterial cellulose nano composite synthesized in the presence of  
809 tripolyphosphate. *Journal of Drug Delivery Science and Technology*, *44*(January), 244–253.  
810 <https://doi.org/10.1016/j.jddst.2017.12.019>

811 Jiang, J., Pi, J., & Cai, J. (2018). The Advancing of Zinc Oxide Nanoparticles for Biomedical  
812 Applications. *Bioinorganic Chemistry and Applications*, *2018*.  
813 <https://doi.org/10.1155/2018/1062562>

814 Jiang, T., Duan, Q., Zhu, J., Liu, H., & Yu, L. (2020). Starch-based biodegradable materials:  
815 Challenges and opportunities. *Advanced Industrial and Engineering Polymer Research*,  
816 *3*(1), 8–18. <https://doi.org/10.1016/j.aiepr.2019.11.003>

817 Jin, M., Chen, W., Li, Z., Zhang, Y., Zhang, M., & Chen, S. (2018). Patterned bacterial cellulose  
818 wound dressing for hypertrophic scar inhibition behavior. *Cellulose*, *25*(11), 6705–6717.  
819 <https://doi.org/10.1007/s10570-018-2041-7>

820 Kamoun, E. A. (2016). N-succinyl chitosan-dialdehyde starch hybrid hydrogels for biomedical  
821 applications. *Journal of Advanced Research*, *7*(1), 69–77.  
822 <https://doi.org/10.1016/j.jare.2015.02.002>

823 Khalid, A., Khan, R., Ul-Islam, M., Khan, T., & Wahid, F. (2017). Bacterial cellulose-zinc oxide  
824 nanocomposites as a novel dressing system for burn wounds. *Carbohydrate Polymers*, *164*,  
825 214–221. <https://doi.org/10.1016/j.carbpol.2017.01.061>

826 Khamrai, M., Banerjee, S. L., & Kundu, P. P. (2017). Modified bacterial cellulose based self-  
827 healable polyelectrolyte film for wound dressing application. *Carbohydrate Polymers*, *174*,  
828 580–590. <https://doi.org/10.1016/j.carbpol.2017.06.094>

829 Khan, S., Chan, H., Won, S., Ikram, M., Ullah, S., Ul-Islam, M., & Han, S. S. (2024). Bacterial  
830 cellulose-turmeric powder composites as potential therapeutic wound dressings. *Industrial*  
831 *Crops and Products*, *211*(February), 118237. <https://doi.org/10.1016/j.indcrop.2024.118237>

832 Kim, S. E., Kim, N. E., Park, S., Choi, J. H., Song, Y., Tumursukh, N.-E., Youn, J., Song, J. E.,  
833 & Khang, G. (2022). Evaluation of calcium phosphate-coated polycaprolactone/graphene  
834 oxide scaffold with macro- and microporous structure for bone tissue engineering. *In Vitro*  
835 *Models*, *1*(3), 261–272. <https://doi.org/10.1007/s44164-022-00026-9>

836 Koburger, T., Hübner, N. O., Braun, M., Siebert, J., & Kramer, A. (2010). Standardized  
837 comparison of antiseptic efficacy of triclosan, PVP-iodine, octenidine dihydrochloride,  
838 polyhexanide and chlorhexidine digluconate. *Journal of Antimicrobial Chemotherapy*,  
839 *65*(8), 1712–1719. <https://doi.org/10.1093/jac/dkq212>

840 Koehler, J., Brandl, F. P., & Goepferich, A. M. (2018). Hydrogel wound dressings for bioactive

841 treatment of acute and chronic wounds. *European Polymer Journal*, 100(January), 1–11.  
842 <https://doi.org/10.1016/j.eurpolymj.2017.12.046>

843 Kondaveeti, S., Bueno, P. V. de A., Carmona-Ribeiro, A. M., Esposito, F., Lincopan, N.,  
844 Sierakowski, M. R., & Petri, D. F. S. (2018). Microbicidal gentamicin-alginate hydrogels.  
845 *Carbohydrate Polymers*, 186(January), 159–167.  
846 <https://doi.org/10.1016/j.carbpol.2018.01.044>

847 Korupalli, C., Li, H., Nguyen, N., Mi, F. L., Chang, Y., Lin, Y. J., & Sung, H. W. (2021).  
848 Conductive Materials for Healing Wounds: Their Incorporation in Electroactive Wound  
849 Dressings, Characterization, and Perspectives. *Advanced Healthcare Materials*, 10(6), 1–13.  
850 <https://doi.org/10.1002/adhm.202001384>

851 Kotcharat, P., Chuysinuan, P., Thanyacharoen, T., Techasakul, S., & Ummartyotin, S. (2021).  
852 Development of bacterial cellulose and polycaprolactone (PCL) based composite for  
853 medical material. *Sustainable Chemistry and Pharmacy*, 20(September 2020), 100404.  
854 <https://doi.org/10.1016/j.scp.2021.100404>

855 Kotcharat, P., Chuysinuan, P., Thanyacharoen, T., Techasakul, S., & Ummartyotin, S. (2022).  
856 Enhanced Performance of Aloe vera-Incorporated Bacterial Cellulose/Polycaprolactone  
857 Composite Film for Wound Dressing Applications. *Journal of Polymers and the  
858 Environment*, 30(3), 1151–1161. <https://doi.org/10.1007/s10924-021-02262-8>

859 Kumari, S., Kumar Annamareddy, S. H., Abanti, S., & Kumar Rath, P. (2017). Physicochemical  
860 properties and characterization of chitosan synthesized from fish scales, crab and shrimp  
861 shells. *International Journal of Biological Macromolecules*, 104, 1697–1705.  
862 <https://doi.org/10.1016/j.ijbiomac.2017.04.119>

863 Lee, M. S., Seo, S. R., & Kim, J. C. (2012). A  $\beta$ -cyclodextrin, polyethyleneimine and silk fibroin  
864 hydrogel containing Centella asiatica extract and hydrocortisone acetate: Releasing  
865 properties and in vivo efficacy for healing of pressure sores. *Clinical and Experimental  
866 Dermatology*, 37(7), 762–771. <https://doi.org/10.1111/j.1365-2230.2011.04331.x>

867 Li, Y., Tian, Y., Zheng, W., Feng, Y., Huang, R., Shao, J., Tang, R., Wang, P., Jia, Y., Zhang, J.,  
868 Zheng, W., Yang, G., & Jiang, X. (2017). Composites of Bacterial Cellulose and Small  
869 Molecule-Decorated Gold Nanoparticles for Treating Gram-Negative Bacteria-Infected  
870 Wounds. *Small*, 13(27), 1–10. <https://doi.org/10.1002/sml.201700130>

871 Liang, Y., Zhao, X., Hu, T., Chen, B., Yin, Z., Ma, P. X., & Guo, B. (2019). Adhesive  
872 Hemostatic Conducting Injectable Composite Hydrogels with Sustained Drug Release and  
873 Photothermal Antibacterial Activity to Promote Full-Thickness Skin Regeneration During  
874 Wound Healing. *Small*, 15(12), 1–17. <https://doi.org/10.1002/sml.201900046>

875 Liang, Y., Zhao, X., Hu, T., Han, Y., & Guo, B. (2019). Mussel-inspired, antibacterial,  
876 conductive, antioxidant, injectable composite hydrogel wound dressing to promote the  
877 regeneration of infected skin. *Journal of Colloid and Interface Science*, 556, 514–528.  
878 <https://doi.org/10.1016/j.jcis.2019.08.083>

879 Liu, K., & Catchmark, J. M. (2020). Bacterial cellulose/hyaluronic acid nanocomposites  
880 production through co-culturing *Gluconacetobacter hansenii* and *Lactococcus lactis* under  
881 different initial pH values of fermentation media. *Cellulose*, 27(5), 2529–2540.  
882 <https://doi.org/10.1007/s10570-019-02924-w>

883 Lu, Y., Wang, Y., Zhang, J., Hu, X., Yang, Z., Guo, Y., & Wang, Y. (2019). In-situ doping of a  
884 conductive hydrogel with low protein absorption and bacterial adhesion for electrical  
885 stimulation of chronic wounds. *Acta Biomaterialia*, 89, 217–226.  
886 <https://doi.org/10.1016/j.actbio.2019.03.018>

887 Lukáč, P., Hartinger, J. M., Mlček, M., Popková, M., Suchý, T., Šupová, M., Závora, J.,  
888 Adámková, V., Benáková, H., Slanař, O., Bartoš, M., Chlup, H., Lambert, L., & Grus, T.  
889 (2019). A novel gentamicin-releasing wound dressing prepared from freshwater fish  
890 *Cyprinus carpio* collagen cross-linked with carbodiimide. *Journal of Bioactive and*  
891 *Compatible Polymers*, 34(3), 246–262. <https://doi.org/10.1177/0883911519835143>

892 Luo, Z., Liu, J., Lin, H., Ren, X., Tian, H., Liang, Y., Wang, W., Wang, Y., Yin, M., Huang, Y.,  
893 & Zhang, J. (2020). In situ fabrication of nano zno/bcm biocomposite based on ma modified  
894 bacterial cellulose membrane for antibacterial and wound healing. *International Journal of*  
895 *Nanomedicine*, 15, 1–15. <https://doi.org/10.2147/IJN.S231556>

896 Malagurski, I., Levic, S., Mitric, M., Pavlovic, V., & Dimitrijevic-Brankovic, S. (2018).  
897 Bimetallic alginate nanocomposites: New antimicrobial biomaterials for biomedical  
898 application. *Materials Letters*, 212, 32–36. <https://doi.org/10.1016/j.matlet.2017.10.046>

899 Malmir, S., Karbalaei, A., Pourmadadi, M., Hamedi, J., Yazdian, F., & Navae, M. (2020).  
900 Antibacterial properties of a bacterial cellulose CQD-TiO<sub>2</sub> nanocomposite. *Carbohydrate*  
901 *Polymers*, 234(July 2019), 115835. <https://doi.org/10.1016/j.carbpol.2020.115835>

902 Mardawati, E., Rahmah, D. M., Rachmadona, N., Saharina, E., Pertiwi, T. Y. R., Zahrad, S. A.,  
903 Ramdhani, W., Srikandace, Y., Ratnaningrum, D., Endah, E. S., Andriani, D., Khoo, K. S.,  
904 Pasaribu, K. M., Satoto, R., & Karina, M. (2023). Pineapple core from the canning  
905 industrial waste for bacterial cellulose production by *Komagataeibacter xylinus*. *Heliyon*,  
906 9(11), e22010. <https://doi.org/10.1016/j.heliyon.2023.e22010>

907 Matica, M. A., Aachmann, F. L., Tøndervik, A., Sletta, H., & Ostafe, V. (2019). Chitosan as a  
908 wound dressing starting material: Antimicrobial properties and mode of action.  
909 *International Journal of Molecular Sciences*, 20(23), 1–33.  
910 <https://doi.org/10.3390/ijms20235889>

911 Michalska-Sionkowska, M., Kaczmarek, B., Walczak, M., & Sionkowska, A. (2018).  
912 Antimicrobial activity of new materials based on the blends of collagen/chitosan/hyaluronic  
913 acid with gentamicin sulfate addition. *Materials Science and Engineering C*, 86(September  
914 2017), 103–108. <https://doi.org/10.1016/j.msec.2018.01.005>

915 Millon, L. E., & Wan, W. K. (2006). The polyvinyl alcohol-bacterial cellulose system as a new  
916 nanocomposite for biomedical applications. *Journal of Biomedical Materials Research -*  
917 *Part B Applied Biomaterials*, 79(2), 245–253. <https://doi.org/10.1002/jbm.b.30535>

918 Mohaghegh, H., Assadi, Z., Derakhshan, A., & Masaeli, E. (2023). Accelerating Full-Thickness  
919 Wound Healing with Bacterial Cellulose-Based Multilayer Composites. *Journal of*  
920 *Pharmaceutical Sciences*. <https://doi.org/https://doi.org/10.1016/j.xphs.2023.09.018>

921 Mohamad, N., Mohd Amin, M. C. I., Pandey, M., Ahmad, N., & Rajab, N. F. (2014). Bacterial  
922 cellulose/acrylic acid hydrogel synthesized via electron beam irradiation: Accelerated burn  
923 wound healing in an animal model. *Carbohydrate Polymers*, 114, 312–320.  
924 <https://doi.org/10.1016/j.carbpol.2014.08.025>

925 Moniri, M., Moghaddam, A. B., Azizi, S., Rahim, R. A., Zuhainis, S. W., Navaderi, M., &  
926 Mohamad, R. (2018). In vitro molecular study of wound healing using biosynthesized  
927 bacteria nanocellulose/ silver nanocomposite assisted by bioinformatics databases.  
928 *International Journal of Nanomedicine*, 13, 5097–5112.  
929 <https://doi.org/10.2147/IJN.S164573>

930 Moradpoor, H., Mohammadi, H., Safaei, M., Mozaffari, H. R., Sharifi, R., Gorji, P., Sulong, A.  
931 B., Muhamad, N., & Ebadi, M. (2022). Recent Advances on Bacterial Cellulose-Based  
932 Wound Management: Promises and Challenges. *International Journal of Polymer Science*,

933 2022. <https://doi.org/10.1155/2022/1214734>  
 934 Mozalewska, W., Czechowska-Biskup, R., Olejnik, A. K., Wach, R. A., Ulański, P., & Rosiak, J.  
 935 M. (2017). Chitosan-containing hydrogel wound dressings prepared by radiation technique.  
 936 *Radiation Physics and Chemistry*, 134, 1–7.  
 937 <https://doi.org/10.1016/j.radphyschem.2017.01.003>  
 938 Naseri-Nosar, M., & Ziora, Z. M. (2018). Wound dressings from naturally-occurring polymers:  
 939 A review on homopolysaccharide-based composites. *Carbohydrate Polymers*, 189(January),  
 940 379–398. <https://doi.org/10.1016/j.carbpol.2018.02.003>  
 941 Negut, I., Grumezescu, V., & Grumezescu, A. M. (2018). Treatment strategies for infected  
 942 wounds. *Molecules*, 23(9), 1–23. <https://doi.org/10.3390/molecules23092392>  
 943 Nunes, S. B., Hodel, K. V. S., Sacramento, G. da C., da Silva Melo, P., Pessoa, F. L. P., Barbosa,  
 944 J. D. V., Badaró, R., & Machado, B. A. S. (2021). Development of bacterial cellulose  
 945 biocomposites combined with starch and collagen and evaluation of their properties.  
 946 *Materials*, 14(2), 1–21. <https://doi.org/10.3390/ma14020458>  
 947 Ochoa, M., Rahimi, R., & Ziaie, B. (2014). Flexible sensors for chronic wound management.  
 948 *IEEE Reviews in Biomedical Engineering*, 7, 73–86.  
 949 <https://doi.org/10.1109/RBME.2013.2295817>  
 950 Orlando, I., Basnett, P., Nigmatullin, R., Wang, W., Knowles, J. C., & Roy, I. (2020). Chemical  
 951 Modification of Bacterial Cellulose for the Development of an Antibacterial Wound  
 952 Dressing. *Frontiers in Bioengineering and Biotechnology*, 8(September), 1–19.  
 953 <https://doi.org/10.3389/fbioe.2020.557885>  
 954 Orlando, I., & Roy, I. (2019). *Cellulose-Based Hydrogels for Wound Healing*.  
 955 [https://doi.org/10.1007/978-3-319-77830-3\\_38](https://doi.org/10.1007/978-3-319-77830-3_38)  
 956 Osorio, M., Velásquez-Cock, J., Restrepo, L. M., Zuluaga, R., Gañán, P., Rojas, O. J., Ortiz-  
 957 Trujillo, I., & Castro, C. (2017). Bioactive 3D-Shaped Wound Dressings Synthesized from  
 958 Bacterial Cellulose: Effect on Cell Adhesion of Polyvinyl Alcohol Integrated In Situ.  
 959 *International Journal of Polymer Science*, 2017. <https://doi.org/10.1155/2017/3728485>  
 960 Ou, K., Liu, Y., Deng, L., Chen, S., Gu, S., & Wang, B. (2024). Covalently grafting polycation  
 961 to bacterial cellulose for antibacterial and anti-cell adhesive wound dressings. *International*  
 962 *Journal of Biological Macromolecules*, 269(P2), 132157.  
 963 <https://doi.org/10.1016/j.ijbiomac.2024.132157>  
 964 Pal, K., K. B. A., & K. M. D. (2006). Starch Based Hydrogel with Potential Biomedical  
 965 Application as Artificial Skin. *African Journal of Biomedical Research*, 9, 23–29.  
 966 Pasaribu, K. M., Gea, S., Ilyas, S., Tamrin, T., & Radecka, I. (2020). Characterization of  
 967 bacterial cellulose-based wound dressing in different order impregnation of chitosan and  
 968 collagen. *Biomolecules*, 10(11), 1–15. <https://doi.org/10.3390/biom10111511>  
 969 Pasaribu, K. M., Gea, S., Ilyas, S., Tamrin, T., Sarumaha, A. A., Sembiring, A., & Radecka, I.  
 970 (2020). Fabrication and in-vivo study of micro-colloidal Zanthoxylum acanthopodium-  
 971 loaded bacterial cellulose as a burn wound dressing. *Polymers*, 12(7).  
 972 <https://doi.org/10.3390/polym12071436>  
 973 Pasaribu, K. M., Ilyas, S., Tamrin, T., Radecka, I., Swingler, S., Gupta, A., Stamboulis, A. G., &  
 974 Gea, S. (2023). Bioactive bacterial cellulose wound dressings for burns with collagen in-situ  
 975 and chitosan ex-situ impregnation. *International Journal of Biological Macromolecules*,  
 976 123118. <https://doi.org/10.1016/j.ijbiomac.2022.123118>  
 977 Petersen, N., & Gatenholm, P. (2011). Bacterial cellulose-based materials and medical devices:  
 978 Current state and perspectives. *Applied Microbiology and Biotechnology*, 91(5), 1277–

979 1286. <https://doi.org/10.1007/s00253-011-3432-y>  
 980 Pormohammad, A., Monych, N. K., Ghosh, S., Turner, D. L., & Turner, R. J. (2021).  
 981 Nanomaterials in wound healing and infection control. *Antibiotics*, *10*(5).  
 982 <https://doi.org/10.3390/antibiotics10050473>  
 983 Portela, R., Leal, C. R., & Pedro, L. (2019). Minireview Bacterial cellulose : a versatile  
 984 biopolymer for wound dressing applications. *Microbial Biotechnology*, *12*(4), 586–610.  
 985 <https://doi.org/10.1111/1751-7915.13392>  
 986 Qiao, H., Guo, T., Zheng, Y., Zhao, L., Sun, Y., Liu, Y., & Xie, Y. (2018). A novel microporous  
 987 oxidized bacterial cellulose/arginine composite and its effect on behavior of  
 988 fibroblast/endothelial cell. *Carbohydrate Polymers*, *184*(August 2017), 323–332.  
 989 <https://doi.org/10.1016/j.carbpol.2017.12.026>  
 990 Radu, C. D., Verestiuc, L., Ulea, E., Lipsa, F. D., Vulpe, V., Munteanu, C., Bulgariu, L., Pasca,  
 991 S., Tamas, C., Ciuntu, B. M., Ciocan, M., Sîrbu, I., Gavrilas, E., Macarel, C. V., & Istrate,  
 992 B. (2021). Evaluation of keratin/bacterial cellulose based scaffolds as potential burned  
 993 wound dressing. *Applied Sciences (Switzerland)*, *11*(5), 1–17.  
 994 <https://doi.org/10.3390/app11051995>  
 995 Rezvaniyan, M., Ahmad, N., Mohd Amin, M. C. I., & Ng, S. F. (2017). Optimization,  
 996 characterization, and in vitro assessment of alginate-pectin ionic cross-linked hydrogel film  
 997 for wound dressing applications. *International Journal of Biological Macromolecules*, *97*,  
 998 131–140. <https://doi.org/10.1016/j.ijbiomac.2016.12.079>  
 999 Rørth, P. (2011). Whence Directionality: Guidance Mechanisms in Solitary and Collective Cell  
 1000 Migration. *Developmental Cell*, *20*(1), 9–18. <https://doi.org/10.1016/j.devcel.2010.12.014>  
 1001 S., N., L., H., & T., S. (2018). Mepilex border comfort: A new 5-layer bordered foam dressing  
 1002 with flex technology. *Wounds UK*, *14*(4), 94–99.  
 1003 <http://www.embase.com/search/results?subaction=viewrecord&from=export&id=L6241074>  
 1004 38  
 1005 Salleh, A., & Fauzi, M. B. (2021). The in vivo, in vitro and in ovo evaluation of quantum dots in  
 1006 wound healing: A review. *Polymers*, *13*(2), 1–18. <https://doi.org/10.3390/polym13020191>  
 1007 Santamaria, A. G., & Amit, N. (2021). Saturation of a dressing applied to an exuding wound: the  
 1008 gap between clinical judgment and laboratory testing. *Wounds International*, *12*(2), 20–26.  
 1009 Sarabahi, S. (2012). Recent advances in topical wound care. *Indian Journal of Plastic Surgery*,  
 1010 *45*(2), 379–387. <https://doi.org/10.4103/0970-0358.101321>  
 1011 Savitskaya, I. S., Kistaubayeva, A. S., Digel, I. E., & Shokatayeva, D. H. (2017).  
 1012 Physicochemical and antibacterial properties of composite films based on bacterial cellulose  
 1013 and chitosan for wound dressing materials. *Eurasian Chemico-Technological Journal*,  
 1014 *19*(3), 255–264. <https://doi.org/10.18321/ectj670>  
 1015 Schneider, L. A., Korber, A., Grabbe, S., & Dissemond, J. (2007). Influence of pH on wound-  
 1016 healing: A new perspective for wound-therapy? *Archives of Dermatological Research*,  
 1017 *298*(9), 413–420. <https://doi.org/10.1007/s00403-006-0713-x>  
 1018 Seiser, S., Janker, L., Zila, N., Mildner, M., Rakita, A., Matiasek, J., Bileck, A., Gerner, C.,  
 1019 Paulitschke, V., & Elbe-Bürger, A. (2021). Octenidine-based hydrogel shows anti-  
 1020 inflammatory and protease-inhibitory capacities in wounded human skin. *Scientific Reports*,  
 1021 *11*(1), 1–13. <https://doi.org/10.1038/s41598-020-79378-9>  
 1022 Shao, W., Liu, H., Liu, X., Wang, S., Wu, J., Zhang, R., Min, H., & Huang, M. (2015).  
 1023 Development of silver sulfadiazine loaded bacterial cellulose/sodium alginate composite  
 1024 films with enhanced antibacterial property. *Carbohydrate Polymers*, *132*, 351–358.

1025 <https://doi.org/10.1016/j.carbpol.2015.06.057>

1026 Shpichka, A., Butnaru, D., Bezrukov, E. A., Sukhanov, R. B., Atala, A., Burdukovskii, V.,  
1027 Zhang, Y., & Timashev, P. (2019). Skin tissue regeneration for burn injury. *Stem Cell*  
1028 *Research and Therapy*, 10(1), 1–16. <https://doi.org/10.1186/s13287-019-1203-3>

1029 Siddiqui, N., Kishori, B., Rao, S., Anjum, M., Hemanth, V., Das, S., & Jabbari, E. (2021).  
1030 Electropsun Polycaprolactone Fibres in Bone Tissue Engineering: A Review. *Molecular*  
1031 *Biotechnology*, 63(5), 363–388. <https://doi.org/10.1007/s12033-021-00311-0>

1032 Singh, I., Arora, R., Dhiman, H., & Pahwa, R. (2018). Carbon quantum dots: Synthesis,  
1033 characterization and biomedical applications. *Turkish Journal of Pharmaceutical Sciences*,  
1034 15(2), 219–230. <https://doi.org/10.4274/tjps.63497>

1035 Song, S., Liu, Z., Abubaker, M. A., Ding, L., Zhang, J., Yang, S., & Fan, Z. (2021). Antibacterial  
1036 polyvinyl alcohol/bacterial cellulose/nano-silver hydrogels that effectively promote wound  
1037 healing. *Materials Science and Engineering C*, 126(November 2020), 112171.  
1038 <https://doi.org/10.1016/j.msec.2021.112171>

1039 Stanescu, P. O., Radu, I. C., Leu Alexa, R., Hudita, A., Tanasa, E., Ghitman, J., Stoian, O.,  
1040 Tsatsakis, A., Gingham, O., Zaharia, C., Shtilman, M., Mezhev, Y., & Galateanu, B.  
1041 (2021). Novel chitosan and bacterial cellulose biocomposites tailored with polymeric  
1042 nanoparticles for modern wound dressing development. *Drug Delivery*, 28(1), 1932–1950.  
1043 <https://doi.org/10.1080/10717544.2021.1977423>

1044 Sulaeva, I., Hettegger, H., Bergen, A., Rohrer, C., Kostic, M., Konnerth, J., Rosenau, T., &  
1045 Potthast, A. (2020). Fabrication of bacterial cellulose-based wound dressings with improved  
1046 performance by impregnation with alginate. *Materials Science and Engineering C*,  
1047 110(August 2019), 110619. <https://doi.org/10.1016/j.msec.2019.110619>

1048 Sun, H., Gao, N., Dong, K., Ren, J., & Qu, X. (2014). Graphene quantum dots-band-aids used  
1049 for wound disinfection. *ACS Nano*, 8(6), 6202–6210. <https://doi.org/10.1021/nn501640q>

1050 Sun, M., Li, D., Xi, Y., Qin, X., Liao, Y., Liu, X., Jia, S., Xie, Y., & Zhong, C. (2024). NIR-  
1051 triggered bacterial cellulose-based wound dressings for multiple synergistic therapy of  
1052 infected wound. *International Journal of Biological Macromolecules*, 259(P1), 129033.  
1053 <https://doi.org/10.1016/j.ijbiomac.2023.129033>

1054 Tan, S. T., & Dosan, R. (2019). Lessons From Epithelialization: The Reason Behind Moist  
1055 Wound Environment. *The Open Dermatology Journal*, 13(1), 34–40.  
1056 <https://doi.org/10.2174/1874372201913010034>

1057 Tudoroiu, E. E., Dinu-Pîrvu, C. E., Kaya, M. G. A., Popa, L., Anuța, V., Prisada, R. M., &  
1058 Ghica, M. V. (2021). An overview of cellulose derivatives-based dressings for wound-  
1059 healing management. *Pharmaceuticals*, 14(12). <https://doi.org/10.3390/ph14121215>

1060 Ul-Islam, M., Khan, S., Ullah, M. W., & Park, J. K. (2015). Bacterial cellulose composites:  
1061 Synthetic strategies and multiple applications in bio-medical and electro-conductive fields.  
1062 *Biotechnology Journal*, 10(12), 1847–1861. <https://doi.org/10.1002/biot.201500106>

1063 Ullah, H., Wahid, F., Santos, H. A., & Khan, T. (2016). Advances in biomedical and  
1064 pharmaceutical applications of functional bacterial cellulose-based nanocomposites. In  
1065 *Carbohydrate Polymers* (Vol. 150). Elsevier Ltd.  
1066 <https://doi.org/10.1016/j.carbpol.2016.05.029>

1067 Wahid, F., Bai, H., Wang, F. P., Xie, Y. Y., Zhang, Y. W., Chu, L. Q., Jia, S. R., & Zhong, C.  
1068 (2020). Facile synthesis of bacterial cellulose and polyethyleneimine based hybrid  
1069 hydrogels for antibacterial applications. *Cellulose*, 27(1), 369–383.  
1070 <https://doi.org/10.1007/s10570-019-02806-1>

1071 Wahid, F., Khan, T., Shehzad, A., Ul-Islam, M., & Kim, Y. Y. (2014). Interaction of  
1072 nanomaterials with cells and their medical applications. *Journal of Nanoscience and*  
1073 *Nanotechnology*, 14(1), 744–754. <https://doi.org/10.1166/jnn.2014.9016>

1074 Walker, M., Hobot, J. A., Newman, G. R., & Bowler, P. G. (2003). Scanning electron  
1075 microscopic examination of bacterial immobilisation in a carboxymethyl cellulose  
1076 (AQUACEL®) and alginate dressings. *Biomaterials*, 24(5), 883–890.  
1077 [https://doi.org/10.1016/S0142-9612\(02\)00414-3](https://doi.org/10.1016/S0142-9612(02)00414-3)

1078 Wang, N., Xu, H., Sun, S., Guo, P., Wang, Y., Qian, C., Zhong, Y., & Yang, D. (2020). Wound  
1079 therapy via a photo-responsively antibacterial nano-graphene quantum dots conjugate.  
1080 *Journal of Photochemistry and Photobiology B: Biology*, 210(July), 111978.  
1081 <https://doi.org/10.1016/j.jphotobiol.2020.111978>

1082 Wang, T., Zhu, X. K., Xue, X. T., & Wu, D. Y. (2012). Hydrogel sheets of chitosan, honey and  
1083 gelatin as burn wound dressings. *Carbohydrate Polymers*, 88(1), 75–83.  
1084 <https://doi.org/10.1016/j.carbpol.2011.11.069>

1085 Wiegand, C., Moritz, S., Hessler, N., Kralisch, D., Wesarg, F., Müller, F. A., Fischer, D., &  
1086 Hipler, U. C. (2015). Antimicrobial functionalization of bacterial nanocellulose by loading  
1087 with polyhexanide and povidone-iodine. *Journal of Materials Science: Materials in*  
1088 *Medicine*, 26(10). <https://doi.org/10.1007/s10856-015-5571-7>

1089 Xia, J., Zhang, H., Yu, F., Pei, Y., & Luo, X. (2020). Superclear, Porous Cellulose Membranes  
1090 with Chitosan-Coated Nanofibers for Visualized Cutaneous Wound Healing Dressing. *ACS*  
1091 *Applied Materials and Interfaces*, 12(21), 24370–24379.  
1092 <https://doi.org/10.1021/acsami.0c05604>

1093 Yan, N., Zhou, Y., Zheng, Y., Qiao, S., Yu, Q., Li, Z., & Lu, H. (2015). Antibacterial properties  
1094 and cytocompatibility of bio-based nanostructured carbon aerogels derived from silver  
1095 nanoparticles deposited onto bacterial cellulose. *RSC Advances*, 5(118), 97467–97476.  
1096 <https://doi.org/10.1039/c5ra15485e>

1097 Yang, M., & Choy, K. leong. (2021). A nature-derived, flexible and three dimensional (3D)  
1098 nano-composite for chronic wounds pH monitoring. *Materials Letters*, 288, 129335.  
1099 <https://doi.org/10.1016/j.matlet.2021.129335>

1100 Yang, X., Wang, Y., Zhou, Y., Chen, J., & Wan, Q. (2021). The application of polycaprolactone  
1101 in three-dimensional printing scaffolds for bone tissue engineering. *Polymers*, 13(16).  
1102 <https://doi.org/10.3390/polym13162754>

1103 Yang, Z., Huang, R., Zheng, B., Guo, W., Li, C., He, W., Wei, Y., Du, Y., Wang, H., Wu, D., &  
1104 Wang, H. (2021). Highly Stretchable, Adhesive, Biocompatible, and Antibacterial Hydrogel  
1105 Dressings for Wound Healing. *Advanced Science*, 8(8), 1–12.  
1106 <https://doi.org/10.1002/advs.202003627>

1107 Yang, Z., Ma, L., Han, X., Xun, X., Li, T., Duan, K., Hu, X., Wan, Y., & Ao, H. (2022). A  
1108 facile, biosynthetic design strategy for high-performance multifunctional bacterial cellulose-  
1109 based dressing. *Composites Part B: Engineering*, 238, 109945.  
1110 <https://doi.org/https://doi.org/10.1016/j.compositesb.2022.109945>

1111 Yi, X., Cheng, F., Wei, X., Li, H., Qian, J., & He, J. (2023). Bioinspired adhesive and self-  
1112 healing bacterial cellulose hydrogels formed by a multiple dynamic crosslinking strategy for  
1113 sealing hemostasis. *Cellulose*, 30(1), 397–411. <https://doi.org/10.1007/s10570-022-04909-8>

1114 Yu, R., Zhang, H., & Guo, B. (2022). Conductive Biomaterials as Bioactive Wound Dressing for  
1115 Wound Healing and Skin Tissue Engineering. In *Nano-Micro Letters* (Vol. 14, Issue 1).  
1116 Springer Singapore. <https://doi.org/10.1007/s40820-021-00751-y>

- 1117 Zhang, L., Yu, Y., Zheng, S., Zhong, L., & Xue, J. (2021). Preparation and properties of  
1118 conductive bacterial cellulose-based graphene oxide-silver nanoparticles antibacterial  
1119 dressing. *Carbohydrate Polymers*, 257(September 2020), 117671.  
1120 <https://doi.org/10.1016/j.carbpol.2021.117671>
- 1121 Zhang, S., Campagne, C., & Salaün, F. (2019). Influence of solvent selection in the  
1122 electrospaying process of polycaprolactone. *Applied Sciences (Switzerland)*, 9(3).  
1123 <https://doi.org/10.3390/app9030402>
- 1124 Zhang, S., Yang, Z., Hao, J., Ding, F., Li, Z., & Ren, X. (2022). Hollow nanosphere-doped  
1125 bacterial cellulose and polypropylene wound dressings: Biomimetic nanocatalyst mediated  
1126 antibacterial therapy. *Chemical Engineering Journal*, 432(October 2021), 134309.  
1127 <https://doi.org/10.1016/j.cej.2021.134309>
- 1128 Zhou, C., Yang, Z., Xun, X., Ma, L., Chen, Z., Hu, X., Wu, X., Wan, Y., & Ao, H. (2022). De  
1129 novo strategy with engineering a multifunctional bacterial cellulose-based dressing for rapid  
1130 healing of infected wounds. *Bioactive Materials*, 13(November 2021), 212–222.  
1131 <https://doi.org/10.1016/j.bioactmat.2021.10.043>
- 1132 Zywicka, A., Fijałkowski, K., Junka, A. F., Grzesiak, J., & El Fray, M. (2018). Modification of  
1133 Bacterial Cellulose with Quaternary Ammonium Compounds Based on Fatty Acids and  
1134 Amino Acids and the Effect on Antimicrobial Activity. *Biomacromolecules*, 19(5), 1528–  
1135 1538. <https://doi.org/10.1021/acs.biomac.8b00183>  
1136  
1137  
1138  
1139