Bacterial Cellulose in Wastewater Treatment

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Contributor: Attilio Converti

Bacterial cellulose membranes have been shown to be efficient as filters for the removal of various contaminants, including biological and chemical agents or heavy metals. Therefore, their use could make an important contribution to bio-based technological development in the circular economy. Moreover, they can be used to produce new materials for industry, taking into consideration current environmental preservation policies aimed at a more efficient use of energy.

Keywords: nanocellulose ; biotechnology ; oleophobic filter ; oily effluents ; fashion industry effluents

1. Introduction

Water resources are essential for industrial activities, energy production, agriculture, and life on earth [1]. In particular, the access to potable water and efficient treatment methods are essential for the prevention of various types of pollution and waterborne diseases [2]. It is possible to reduce the load of pollutants through the interconnection of different industrial sectors, so that their by-products are treated and reused, and waste production is minimized, with the perspective of becoming raw material in a new production cycle [3].

Industrial pollutants such as dyes, synthetic chemicals, heavy metals, oils, microplastics and others can have different origins and properties, and many of them accumulate in the environment over time, causing increasing damage [4]. According to Rajasulochana and Preethy [5], the methods of industrial wastewater treatment vary according to several factors, including volume, constitution of the effluent and limits imposed by environmental legislations. Increased research on renewable energy and energy saving technologies has favored the development of new processes and materials as alternatives to treat complex wastewater [6][7].

Many publications describe the application of membrane filtration for the treatment of wastewaters, especially the oily ones. Membrane technologies such as microfiltration, ultrafiltration and nanofiltration are increasingly used for the treatment and purification of wastewater and oily emulsions, as well as for the supply of clean water. However, the most commercially available membranes are made with synthetic polymers of fossil origin [8][9], which require large amounts of solvents and chemicals. In this sense, interest is growing in the production of membranes based on natural polymers, especially those based on cellulose.

Among the possible new biotechnological materials, cellulose stands out, and in particular, vegetable cellulose (VC), which is the main biopolymer produced by plants. Although plants are currently the most abundant source of cellulose, several types of bacteria, mainly belonging to the genera *Sarcina*, *Gluconacetobacter* and *Agrobacterium* have also been found to produce it as an alternative source [10][11]. The potential of bacterial cellulose (BC) goes far beyond its existing applications, especially with a view to its large-scale production as a low-cost raw material to provide industrial functionality in various sectors in a sustainable way [12]. BC is highly porous and has a reticular structure with small pore size, which is ideal for fine filtration purposes. However, there is still a limited number of works in the literature on its use as a raw material for filtration membranes to be applied to water treatment [6][13][14][15][16].

2. Water Resources and Energy Management

Water and energy consumptions can be closely linked (**Figure 1**) as they are both essential for industrial production. Water is essential for the production and refinement of various types of motor fuels and for the extraction of coal and oil, but it is also widely used in the cooling process in different sectors and in the generation of hydroelectric power generation, one of the most popular forms of electricity supply in the world [17][18]. Energy is essential for drinking water production, wastewater treatment, water transport and distribution to both industry and population. Therefore, the conscious use of water and energy is a global concern, which has led to the creation of new technologies, making wastewater treatment and use of clean energy essential areas for sustainable development [19][20].

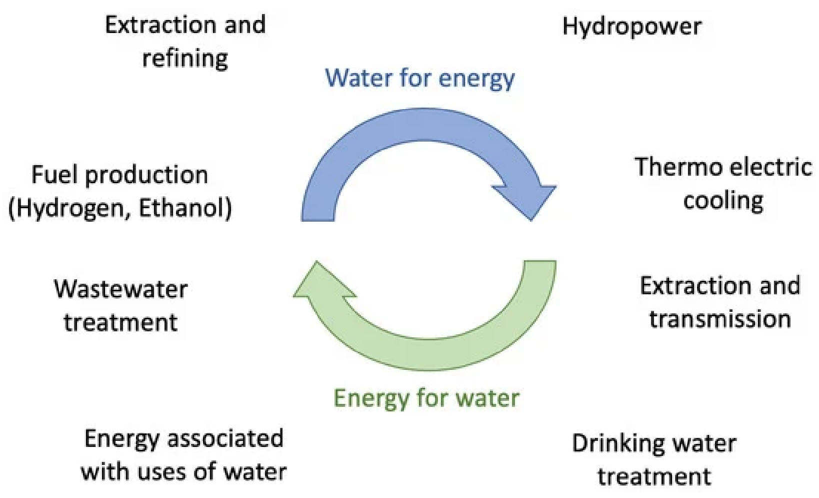

Figure 1. Water and energy consumption cycle.

3. Water Contamination

Over the years, mankind has produced a large amount of waste, resulting in a deterioration of life quality [21]. **Figure 2** shows how this damage to the environment has been caused by several factors including sediment, biological and chemical pollution [22].

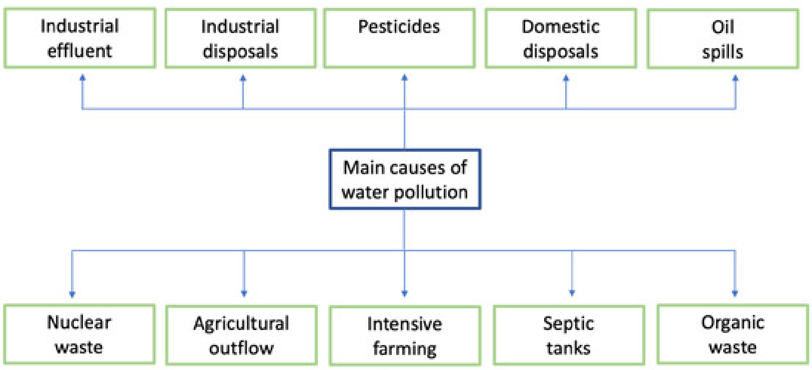

Figure 2. Main causes of water effluent pollution.

Oil, among these pollutants, is one of those that most pollute the environment and are most harmful to nature. Moreover, the residues of its derivatives contain significant quantities of mineral oil, which is highly resistant to biochemical decomposition. These pollutants can be found in their free form or as emulsions made up of complex mixtures of water, oil and additives including emulsifiers, corrosion inhibitors and anti-foaming agents. While free or suspended oils can be easily separated from the aqueous phase of these wastes by simple physical processes, emulsions are chemically stabilized and can only be separated by more complex, and therefore more expensive, separation methods [23][24][25].

Chemical pollution has cumulative effects that cause enormous damage to terrestrial and aquatic life, as well as to the ecosystem and food chain [26]. The treatment and remediation of chemically polluted sites constitute one of the major barriers to be overcome, as in addition to taking time, they have a high cost [9].

4. Filtration Membranes

Filtration is a technique that aims to mechanically selectively separate solid particles or large molecular structures from a liquid suspension with the help of a membrane with specific porosity that acts as a porous bed to perform phase separation [27][28]. They can be produced in a wide variety of configurations and structures depending on the volume and quality of water to be filtered and the separation flow [28].

In industrial filtration processes, filter membranes made up of natural or synthetic fabrics are generally used [29] to retain solid particles suspended in the air, such as microorganisms, specific gases, minerals or other volatile substances, or to treat the effluents from the textile and petrochemical industries [30]. Specific fabrics are also used in hoods, exhausts and outlets of industrial chimneys, thanks to their ability to withstand high temperatures [29][30].

The economic and practical importance of the choice of synthetics membranes is that they can be engineered to result in membranes with specific characteristics that may optimize the industrial filtration process, in addition to reducing costs for the company, such as those related to filter purchase, maintenance and energy consumption [29].

The efficiency of a filter membrane is directly related to the pore diameter and the specific parameters of the material used [31], since it establishes the exact size of the particle that can pass through the membrane. This defines their specific classification and application, as shown in **Table 1**.

Table 1. Classification of membranes and their respective applications.

Classification	Application	Pore Size (nm)	Reference
Microfiltration (MF)	**Removal of suspended solids, protozoa, and bacteria**	**100–5000**	[32]
Ultrafiltration (UF)	**Removal of viruses and colloids**	**2–100**	[33]
Nanofiltration (NF)	**Removal of water hardness, heavy metals, and dissolved organic matter**	**0.5–2**	[33]
Reverse osmosis	**Desalination, water reuse and ultra-pure water production**	**0.2–1**	[34]

5. Bacterial Cellulose Membranes

Cellulose, composed of glucose monomers, is the main structural biopolymer of plants, but it can be also produced by other life forms such as bacteria, fungi and even protozoa. Such a natural bioproduct, whose great technological importance is justified by its wide variety of applications [35], is the most abundant in the world, with an estimated annual production of 10^{11} tons, most of which is of vegetable origin [36].

According to Donini et al. [35], bacterial cellulose (BC) differs from vegetable cellulose (VC) in that it has nanometric rather than micrometric size, better mechanical properties such as higher tensile strength and flexibility, higher purity given that VC is naturally linked to hemicellulose and pectin, higher crystallinity, water retention capacity, biocompatibility, biodegradability and biological adaptability [37][38]. These peculiar properties (**Figure 3**), attributable to the inter and intramolecular hydrogen bonds that hold the polymer chains together [28], make BC an extremely versatile biopolymer that can be used in various sectors of economic importance.

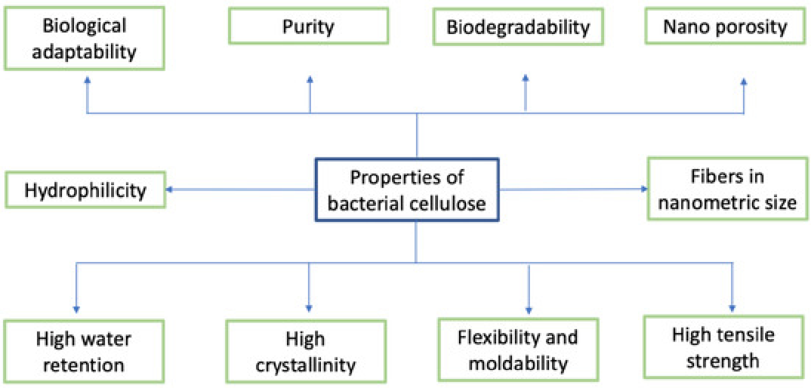

Figure 3. Main properties of bacterial cellulose.

BC is a natural biomaterial (**Figure 4**) that has aroused much interest in research because, in addition to having the interesting properties mentioned above, it can be subject to different types of modifications depending on the desired application, giving rise to new composites or polymer blends [39][40][41].

Figure 4. Picture of a bacterial cellulose membrane. Reproduced with permission from [41], Universidade Católica de Pernambuco, 2020.

To form the membrane fiber, several adjacent fibrils join through hydrogen bonds to form 40 to 60 nm thick layers. These intertwined fibers form a gelatinous film called Zooglea (**Figure 5**) [42][43], which, due to being made up of about 98% water and having a lower density than water, remains on the surface of the culture medium. The thickness of the polymer membrane formed will depend on the fermentation time [12][44].

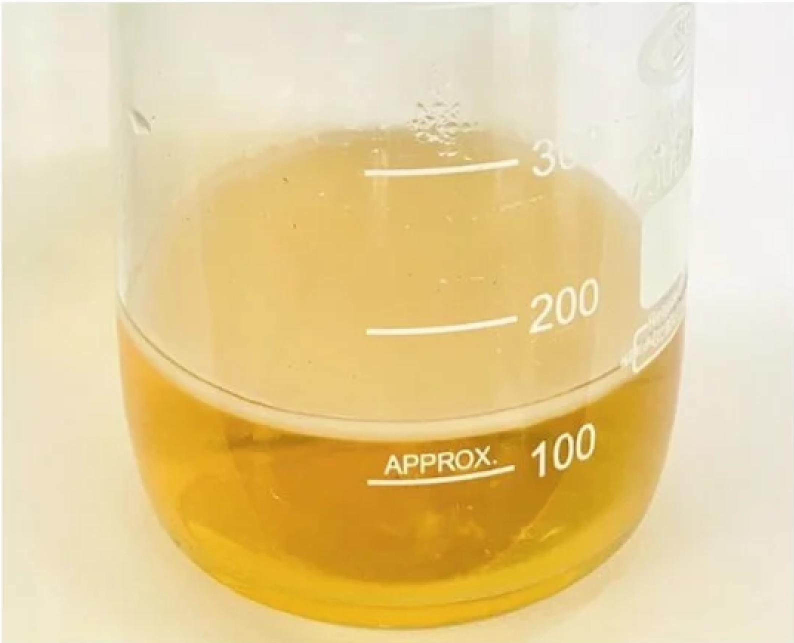

Figure 5. Picture showing bacterial growth and formation of bacterial cellulose membrane as a flotation promoter. Reproduced with permission from [45], Universidade Federal de Pernambuco, 2020.

6. Bacterial Cellulose in Wastewater Treatment

As BC has hydrophilic and oleophobic properties [31]. During the filtration of oily effluents or emulsions only water droplets pass through the nanometric pores of the membrane at a certain pressure applied to the system, which means that the oil remains on its surface (**Figure 6**).

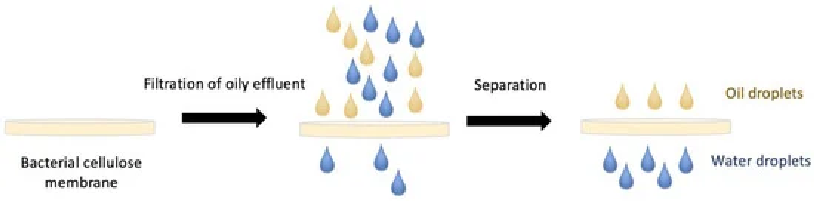

Figure 6. Schematic representation of oil–water separation process using BC as a filter.

For oil/water emulsions, some studies have shown that certain modifying agents are able to make BC membranes hydrophobic, thus enhancing their oil/water selectivity [16]. This is an attempt to obtain a better filtration yield according to the filtrate specifications.

Moreover, thanks to its nanoporous structure and its susceptibility to chemical derivatization, BC is suitable for the removal of heavy metal ions from aqueous solution [46]. In this context, grafting of cellulose-based materials with functional groups, such as amino, carboxyl and thiol groups, has been proposed as a strategy to enhance their adsorption capacity [47]. However, other reports have shown that the capacity of these altered materials to adsorb metal ions, as well as their mechanical properties, still need further improvement through new derivatization strategies [6][46]. For this purpose, studies have been focusing on improving the flexibility and mechanical strength of these materials compared with the simple BC [48], the latter being an extremely important property when they are used to produce reusable membranes. Another strategy to modify the BC structure is to increase the pore size by preparing composite materials, since its dense nanofibrillar structure can impair the performance of the separation process due to liquid infiltration that reduces its efficiency and the possibility of reuse. Furthermore, such a procedure reduces energy consumption because separation takes place using gravity alone, i.e., without the need to apply any additional pressure [49].

Importantly, all these modifications to the polymer can be done alone or in combination, depending on both the desired BC (composite or blend) properties and the specific application [39][40].

The few studies conducted so far using BC as a filter membrane (**Table 2**) suggest that it has enormous unexplored potential, with particular reference to its low sensitivity to water, so that it does not decompose in contact with substances in liquid state, high degree of porosity, low density and nanofiber structure that allow nanoscale filtration [12][50].

Table 2. Studies relating to the use of bacterial cellulose (BC) as filter membrane to treat effluents.

Title	Description	Reference
Surface modification of bacterial cellulose aerogels' web-like skeleton for oil/water separation	**Nanofibers of BC aerogels were modified on their surfaces by trimethylsilylation derivatization followed by freeze-drying. The resulting hydrophobic and oleophilic aerogels were shown to remove a wide range of organic solvents and oils, with potential use in cleaning up oil spills in the marine environment.**	[16]
Polyethyleneimine-bacterial cellulose bioadsorbent for effective removal of copper and lead ions from aqueous solution	**Reductive amination with polyethyleneimine allowed to transform the BC membrane into a bioadsorbent for the removal of heavy metal ions [Cu (II) and Pb (II)] from wastewater.**	[46]
Facile fabrication of flexible bacterial cellulose/silica composite aerogel for oil/water separation	**A silica aerogel composite was prepared by BC modification with methylene diphenyl diisocyanate to increase its hydrophobicity and flexibility, thus making it a promising oil sorbent.**	[48]
Preparation and characterization of a bi-layered nanofiltration membrane from a chitosan hydrogel and bacterial cellulose nanofiber for dye removal	**A membrane was developed by grafting multi-walled carbon nanotubes into BC molecular chains. The BC powder was dissolved in a solution of LiCl and *N*,*N*-dimethylacetamide, and stannous octoate was used as a reaction catalyst. The membrane exhibited greater tensile strength, Young's modulus and pressure resistance, which practically tripled its flow rate and allowed for a yield of dye removal above 90%.**	[51]
Design of reusable novel membranes based on bacterial cellulose and chitosan for the filtration of copper in wastewaters	**Chitosan-modified BC membranes were developed by ex situ (BC immersed in solutions with different chitosan concentrations) or in situ (addition of chitosan solutions to BC production medium) techniques for Cu (II) ions adsorption. The membrane produced by the ex situ technique showed greater efficiency in removing ions.**	[52]

Title	Description	Reference
Removal of U(VI) from aqueous solution using phosphate functionalized bacterial cellulose as efficient adsorbent	**BC membranes were modified by grafting phosphate functional groups soaking them in dimethylacetamide and urea. Membrane characterization confirmed the successful incorporation of phosphate groups. Due to the presence of polar hydroxyl groups and electrostatic attraction, the membranes at pH between 4 and 8 were able to adsorb 9 mg/g of U (IV) ions.**	[53]
Bacterial cellulose membranes for environmental water remediation and industrial wastewater treatment	**BC was produced and cleaned with NaOH to be used as a filter membrane for the treatment of microbiologically contaminated effluents (*Escherichia coli*) and dyes from the textile industry. BC membranes showed better results than the commercial ones, removing 100% of cells present in the effluent and being able to be reused for 10 cycles without loss of efficiency.**	[54]
Impact of incubation conditions and post-treatment on the properties of bacterial cellulose membranes for pressure-driven filtration	**Studies on the permeation properties of BC derivatized with poly-oxyethylene were carried out to determine the filtration efficiency of both dry and wet membranes at different pressures and water flow rates.**	[28]
Film-like bacterial cellulose/cyclodextrin oligomer composites with controllable structure for the removal of various persistent organic pollutants from water	**A film-like water purifier, prepared by loading cyclodextrin oligomer onto ultrafine BC, was described. The system showed high and stable adsorption capacity toward various target pollutants such as phenol, bisphenol A, glyphosate and 2,4-dichlorophenol.**	[55]
Bacterial cellulose-polyaniline porous mat for removal of methyl orange and bacterial pathogens from potable water	**BC membranes were modified with polyaniline by in situ oxidative polymerization and posterior lyophilization. BC was applied to remove methyl orange dye and bacterial cells present in drinking water. Membranes showed an absorption capacity of approximately 300 mg/g and antimicrobial activity, reducing the microbial load present in the effluent by up to four times.**	[56]

7. Conclusions and Perspectives

Bacterial cellulose (BC) is considered an eco-friendly and extremely versatile biopolymer, and this is why studies have increased over the years that envisage its use in the form of filter membranes for wastewater treatment. Studies showed the great potential of BC membranes, produced in standard or alternative culture media by single bacterial species or microbial consortia. Thanks to their peculiar characteristics, mainly their nanofibrillar structure, they have proven effective as filters to retain small particles and have been successful in the treatment of industrial effluents, in particular those of the petroleum industry. Characteristics of BC such as high water retention and tensile strength make it an excellent sustainable, biocompatible and biodegradable porous filter bed.

Until now, no reports are available on a direct relationship between BC membrane filtration and related energy expenditure. Further studies are needed to make these membranes resistant to higher flow rates and pressures, so that they can replace today's methods on an industrial and ecofriendly scale. In fact, it is expected that this technology will allow a reduction in energy and maintenance costs, a possible improvement in the treatment and a lower emission of pollutants.

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