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UTILIZATION OF KOMBUCHA RESIDUE FOR THE PRODUCTION OF NANOCELLULOSE AND FUNCTIONAL HYDROGELS CONTAINING FREE AND NANOSTRUCTURED PLANT EXTRACT[1]

APROVEITAMENTO DO RESÍDUO DE KOMBUCHA PARA PRODUÇÃO DE NANOCELULOSE E HIDROGÉIS FUNCIONAIS CONTENDO EXTRATO VEGETAL LIVRE E NANOESTRUTURADO

Elisandra da Silva Pena da Fonseca[2], Walter Paixão de Sousa Filho[2], Larissa da Silva Silveira[2], Luiz Fernando Rodrigues Junior[2], Daniel Assumpção Bertuol[3], Michele Rorato Sagrillo[2] e Liana da Silva Fernandes[2]

ABSTRACT

Bacterial cellulose, a type of nanocellulose (BNC) obtained from scoby, a by-product of the Kombucha fermentation process, represents a sustainable and high-value alternative to plant cellulose due to its high purity, mechanical strength and biocompatibility. This study aimed to optimize the purification process of the scoby to obtain cellulose and subsequently develop functional hydrogels based on nanocellulose incorporating olive leaf extract in its free and nanoencapsulated forms, to obtain a hydrogel with healing potential for therapeutic use in skin lesions. The scoby was subjected to a purification process and characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD). In parallel, a nanoemulsion containing olive leaf extract was developed and physicochemically characterized in terms of particle size, polydispersity index, and zeta potential, and subsequently incorporated into nanocellulose-based hydrogels. The characterization of nanocellulose by SEM and XRD revealed a three-dimensional nanofibrillar morphology and a high degree of crystallinity. The nanoemulsion presented an average particle diameter of 164.2 nm, a polydispersity index of 0.21, and a zeta potential of -18.2 mV, parameters that indicate moderate colloidal stability and good particle size uniformity.. The hydrogels developed with the incorporation of the nanoemulsion and free extract exhibited good consistency, transparency, and water retention capacity, characteristics ideal for topical applications. It is concluded that BNC derived from scoby serves as a renewable biopolymer precursor for the development of functional healing hydrogels, combining sustainability, nanotechnology, and therapeutic efficacy.

Keywords: Bacterial cellulose; Dressings; Nanoemulsion; Sustainability; Scoby.

RESUMO

A celulose bacteriana, um tipo de nanocelulose (BNC) obtida a partir do scoby, resíduo de origem do processo de fermentação da Kombucha, representa uma possibilidade sustentável, com alto valor agregado em comparação a celulose vegetal, devido ao seu alto grau de pureza, resistência mecânica e biocompatibilidade. O estudo objetivou otimizar o processo de purificação do scoby para obtenção de uma

1 Part of the Doctoral Thesis of the Graduate Program in Nanosciences, Franciscan University - UFN.

2 Graduate Program in Nanosciences, Franciscan University - UFN, Santa Maria, RS, Brazil. E-mails: elisndrapena@ufn.edu.br; walter.paixao@ufn.edu.br; larissa.silveira@ufn.edu.br; luiz.fernando@ufn.edu.br; sagrillomr@ufn.edu.br; liana@ufn.edu.br. ORCID: https://orcid.org/0009-0007-1025-699X; https://orcid.org/0000-0001-5962-4908; https://orcid.org/0000-0003-4460-9857; https://orcid.org/0000-0002-5753-5503; https://orcid.org/0000-0001-5659-159X; https://orcid.org/0000-0003-4745-7617

3 Environmental Processes Laboratory (LAPAM), Department of Chemical Engineering - Federal University of Santa Maria (UFSM). E-mail: dbertuol@gmail.com. ORCID: https://orcid.org/0000-0002-4646-7816

celulose e, posteriormente, desenvolver hidrogéis funcionais a base de nanocelulose e incorporar extrato de folhas de oliveira em sua forma livre e nanoestruturada, a fim de obter um hidrogel com potencial curativo para uso terapêutico em lesões cutâneas. O scoby foi submetido ao processo de purificação, caracterização por microscopia eletrônica de varredura (MEV) e difração de raios X (DRX). Paralelamente, foi desenvolvida uma nanoemulsão contendo extrato de folhas de oliveira e caracterizada físico-quimicamente quanto ao tamanho de partícula, índice de polidispersão, potencial zeta e após, incorporada nos hidrogéis a base de celulose bacteriana. Os resultados da caracterização da nanocelulose por MEV e DRX apresentaram morfologia tridimensional de nanofibrilas e alto grau de cristalinidade. A nanoemulsão apresentou diâmetro médio de 164,2 nm; índice de polidispersão de 0,21 e potencial zeta de -18,2 mV; parâmetros que indicam estabilidade coloidal moderada e boa uniformidade do tamanho das partículas. Os hidrogéis desenvolvidos com a incorporação da nanoemulsão e do extrato livre apresentarem boa consistência, transparência e retenção de água, características que são ideias para aplicações tópicas. Conclui-se que a BNC derivada de scoby serve como um precursor de biopolímero renovável para o desenvolvimento de hidrogéis funcionais de cura, unindo sustentabilidade, nanotecnologia e eficácia terapêutica.

Palavras-chave: *Celulose bacteriana; Curativos; Nanoemulsão; Sustentabilidade; Scoby.*

1 INTRODUCTION

Bacterial cellulose, a specific form of nanocellulose (BNC) derived from scoby, a by-product discarded during Kombucha production, has been explored as a high-value natural biopolymer with properties superior to those of plant cellulose, mainly due to its high purity, mechanical strength, and flexibility (Gagliardi *et al*., 2025). The Kombucha fermentation process is carried out by a symbiotic community of bacteria and yeasts that produces a thick membrane of BNC, which is generally considered an economically worthless by-product but has recently become a target for valorization strategies within the concept of the circular economy (Cubas *et al*., 2023; Gagliardi *et al*., 2025).

Also known as microbial cellulose, BNC is synthesized by various genera of Gram-negative bacteria, including *Acetobacter*, *Achromobacter*, *Aerobacter*, *Agrobacterium*, *Alkaligenes*, *Azotobacter*, *Pseudomonas*, *Rhizobium*, *Rhodobacter*, *Sarcina*, and *Salmonella* (Sadalage; Pawar, 2021). Among these, *Gluconacetobacter xylinus* is the most widely used species for BNC production (Qiu *et al*., 2016). However, other species can also synthesize nanocellulose, such as *G. hansenii* (Dos Reis *et al*., 2018), *G. kombuchae* (Saska *et al*., 2017), *K. europaeus*, and the acid-resistant strain *K. medellinensis* (Osorio *et al*., 2018).BNC consists of a unique interlaced network of fine fibers with a composition similar to that of plant cellulose, but without lignin, pectin, or hemicellulose (Wiegand *et al*., 2015).

Studies have confirmed that BNC obtained from the scoby can be processed into biodegradable films with potential application as active food packaging, due to its ability to incorporate bioactive compounds such as polyphenols, which provide antioxidant properties (Doğan, 2023; Patil *et al*., 2024). Moreover, the nanofibrillar structure and high crystallinity of BNC facilitate its use in active encapsulation, controlled compound release, and as a matrix for probiotic microorganism immobilization (Charoenrak *et al*., 2023; Gagliardi *et al*., 2025). It has also been highlighted for its flexibility and water absorption capacity, essential characteristics for managing exudate and maintaining a moist environment in wound healing (Gagliardi *et al*., 2025).

From a sustainability perspective, the use of scoby represents a renewable, low-cost, and environmentally friendly alternative, reusing agro-industrial residues as raw materials for various applications (Cubas *et al*., 2023). BNC has been increasingly explored beyond the food sector - in tissue engineering, 3D bioprinting, and as a substitute for synthetic plastics - due to its biocompatibility and excellent mechanical properties (Pillai *et al*., 2021; Ramírez *et al*., 2022; Gagliardi *et al*., 2025).

In this context, BNC can be used as a wound dressing material, either alone or as a matrix for incorporating antimicrobial agents (Gagliardi *et al*., 2025). Olive leaf extract, in turn, possesses well-documented therapeutic properties attributed to its rich polyphenolic content. Its main biological activities include antioxidant, anti-inflammatory, antimicrobial, neuroprotective, cardioprotective, hypoglycemic, hypolipidemic, and anticancer effects (Barbaro *et al*., 2014; Filardo *et al*., 2024). Thus, olive leaf extract is of great interest for incorporation into dermatological formulations due to its antioxidant, antimicrobial, and wound-healing potential (Hashmi *et al*., 2015; Magyari-Pave *et al*., 2024).

The association of this extract with BNC-based hydrogels is particularly advantageous, as these biomaterials exhibit adjustable porosity, high water retention capacity, and tunable mechanical properties (Ramírez *et al*., 2022; Cubas *et al*., 2023). Furthermore, their transparency enables visual monitoring of the wound-healing process without the need for frequent dressing changes (Charoenrak *et al*., 2023).

This work is directly aligned with the Sustainable Development Goals (SDGs) proposed in the 2030 Agenda. The research contributes to SDG 12 (Responsible Consumption and Production) by adding value to an agro-industrial residue - the scoby from Kombucha production - transforming it into a functional biopolymer and promoting the circular economy. Additionally, the study addresses SDG 3 (Good Health and Well-Being), since the final product is a hydrogel with therapeutic potential for the treatment of skin injuries. Finally, the project supports SDG 9 (Industry, Innovation and Infrastructure) by fostering scientific research and the development of an innovative nanotechnological solution with direct application in the healthcare field (UN, 2015).

By combining science, sustainability, and nanotechnology, a promising alternative emerges for the development of advanced wound dressings. Therefore, this study aimed to optimize and standardize the purification process of BNC and subsequently use it as a base for the development of hydrogels incorporating a hydroalcoholic extract with therapeutic properties, both in its free and nanoencapsulated forms, in order to obtain functional dressings that integrate the mechanical properties of nanocellulose with the therapeutic potential of the extract for possible application in skin lesion treatment.

2 METHODOLOGY

2.1 OBTAINING BACTERIAL CELLULOSE

The BNC used in this study was obtained from residues of a symbiotic culture of bacteria and yeast (scoby), derived from the fermentation process used to produce Kombucha-based beverages. The material was provided through a partnership with Yam! Kombucha Ltda, located in Santa Maria, Rio Grande do Sul, Brazil. The samples were collected after the biomass was discarded at the end of the fermentation cycle.

2.1.1 Purification of bacterial cellulose

The purification process of BNC was performed based on the methodology described by Han *et al*. (2018), with adaptations to optimize and standardize the procedure. For each stage of purification, approximately 150 g of scoby were used.

In the first step, 150 g of scoby were weighed and immersed in 500 mL of a 3% (w/v) sodium hydroxide (NaOH) solution under controlled heating (25-30 °C) and constant mechanical stirring for 90 minutes.

In the next stage, the samples were washed with distilled water, and the pH was adjusted to the range of 3.0-4.0 using a 3% (v/v) acetic acid solution. During this stage, the samples were maintained under the same heating and stirring conditions for 30 minutes. At the end of the process, the nanocellulose was thoroughly washed with ultrapure water and stored in a sterile, transparent glass flask for later use.

In the final step, the samples underwent a fiber relaxation process using an ultrasonic processor (model VCX 750). The BNC was immersed in 200 mL of ultrapure water, and the process began at a low amplitude of 20%, followed by an increase to 40% for 15 minutes. To evaluate the effect of time on processing, tests were conducted at different durations (5, 10, 15, and 20 minutes), maintaining a constant amplitude of 20%. This allowed a detailed analysis of how processing time influenced the BNC properties.

2.2 CHARACTERIZATION OF BACTERIAL CELLULOSE

2.2.1 Scanning Electron Microscopy (SEM)

The surface morphology of the BNC was analyzed by Scanning Electron Microscopy (SEM) using a Tescan Analytics VEGA 3-SBU microscope, with the aim of observing the three-dimensional structure, fiber organization, and material porosity. The samples were previously dried in a desiccator, then mounted on metallic stubs with conductive tape and sputter-coated with gold. The images were obtained at different magnifications, ranging from 500× to 10,000×.

2.2.2 X-Ray Diffraction (XRD)

The structural analysis of the BNC was performed using X-Ray Diffraction (XRD) with a Bruker D2 Advance diffractometer equipped with a copper tube operating at 30 kV and 30 mA, in θ-θ geometry. The goniometer scan speed was 0.1°/s within a 2θ range of 5° to 70°. This technique allowed the assessment of the crystallinity degree and potential structural modifications of the samples.

2.3 OBTAINING THE HYDROALCOHOLIC EXTRACT OF OLIVE LEAVES

The hydroalcoholic extract used in this study consisted of a blend of olive leaves, produced by our research group, the *Laboratory of Bioprospecting and Experimental Biology (LABBIE)* - *Franciscan University (UFN)*, and protected under patent registration number BR 1020230076416.

2.4 OBTAINING THE NANOEMULSION CONTAINING THE HYDROALCOHOLIC EXTRACT

The nanoemulsion containing the hydroalcoholic extract with the blend of olive leaves was also developed by our research group (LABBIE) and is protected under patent registration number BR 1020240214153.

2.5 PHYSICOCHEMICAL CHARACTERIZATION OF THE NANOEMULSION CONTAINING EXTRACT

2.5.1 Mean particle diameter and polydispersity index (PDI)

The mean particle diameter and the polydispersity index (PDI) were determined using Dynamic Light Scattering (DLS) with a Zetasizer® instrument. This technique measures particle diffusion due to Brownian motion and converts it into particle size and size distribution data. The sample was diluted 500-fold in ultrapure water (Milli-Q®), previously filtered through a 0.45 µm membrane, and the measurements were performed in triplicate.

2.5.2 Zeta potential

The zeta potential was determined using the electrophoretic light scattering technique with a Zetasizer® instrument, and the results were expressed in millivolts (mV). The sample was diluted 500-fold in a 10 mmol/L NaCl solution, previously filtered through a 0.45 µm membrane, and analyzed in triplicate.

2.5.3 pH evaluation

The pH of the nanoformulation was measured using a potentiometer (DM-22, Digimed®) previously calibrated with pH 4.0 and 7.0 buffer solutions. The electrode was immersed directly in the formulation, and the results were expressed as the mean of three measurements.

2.6 PRODUCTION OF BACTERIAL CELLULOSE-BASED HYDROGELS

The hydrogels were prepared following the protocol described by Moraes (2018), with adaptations according to the objectives of this study. Three types of BNC-based hydrogels were developed: 1) Pure BNC hydrogel; 2) BNC hydrogel containing hydroalcoholic extract; 3) BNC hydrogel containing nanoemulsion with extract.

2.6.1 Preparation of pure BNC hydrogel

After the purification process, the cellulose membranes were ground and passed through a mesh 37 sieve to remove excess water, resulting in a BNC paste.In the next step, Nipagin® (used as a preservative), the cellulose paste, and deionized water were added to a beaker. The system was maintained under heating and constant mechanical stirring. Subsequently, Natrosol® 250 was incorporated to provide the appropriate consistency to the hydrogel.

Table 1 - Concentration (%) of reagents used to prepare approximately 50 g of BNC hydrogel.

Reagents	Concentration (%)
Nipagin®	0.10
Natrosol® 250	4.0
Bacterial cellulose	5.0
Deionized water q.s.p.	41.0

Source: Author's elaboration.

2.6.2 Preparation of BNC hydrogel containing hydroalcoholic extract

Following the same procedure, the BNC hydrogel containing extract was prepared. At the end of the process, the hydroalcoholic extract of olive leaves was added.

Table 2 - Concentration (%) of reagents used to prepare approximately 50 g of BNC hydrogel with extract.

Reagents	Concentration (%)
Nipagin®	0.10
Natrosol® 250	4.0
Bacterial cellulose	5.0
Extract/Nanoformulation	5.0
Deionized water q.s.p.	36.0

Source: Author's elaboration.

2.6.3 Preparation of BNC hydrogel containing nanoemulsion with hydroalcoholic extract

For the preparation of the hydrogel containing the nanoemulsion with the hydroalcoholic extract, the same preparation protocol was used, and at the end, the corresponding amount of nanoemulsion was added as described in Table 2.

3 RESULTS AND DISCUSSION

3.1 OBTAINING AND PURIFICATION OF BNC

Figure 1 shows the BNC membrane obtained from the Kombucha residue (scoby) after undergoing the purification steps. A gelatinous and translucent membrane was formed, exhibiting a whitish to slightly yellowish coloration, which are characteristic features of bacterial cellulose following the purification process aimed at removing the impurities present in the raw scoby.

Figure 1 - BNC membrane after the purification process.

Source: Author's elaboration.

BNC membranes, after undergoing the purification process, exhibit high structural purity, free from plant contaminants such as lignin and hemicellulose, and present a well-organized three-dimensional nanofibrillar network. These characteristics result in excellent transparency, high crystallinity, and porosity, which provide great water retention capacity, mechanical strength, flexibility, and biocompatibility, without toxicity risks. Such features make bacterial nanocellulose suitable for various biomedical and cosmetic applications (Chen *et al*., 2022; Campano *et al*., 2025).

The literature reports that an effective purification process for BNC completely removes microbial residues and impurities, while preserving the integrity of the nanofibrillar matrix and maintaining its physicochemical properties (Popa *et al*., 2022; Campano *et al*., 2025). This structural integrity facilitates chemical modification and surface functionalization of BNC, allowing the incorporation of bioactive compounds, thereby expanding its potential use in formulations for wound healing, hydration, and controlled release of active ingredients (Qian *et al*., 2023; Campano *et al*., 2025).

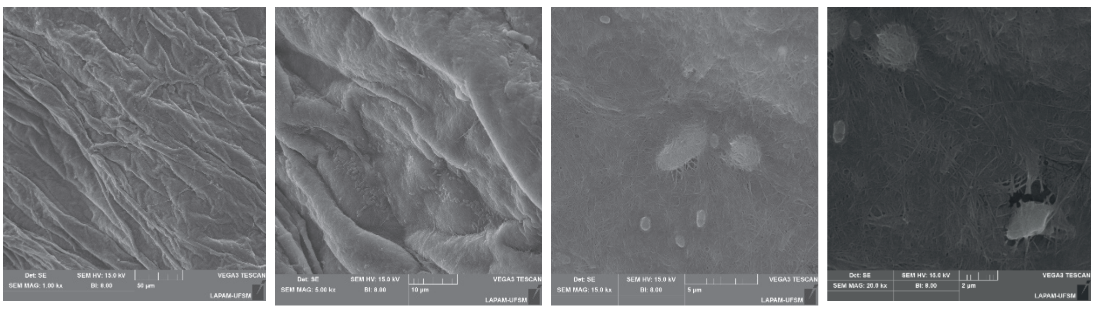
3.2 CHARACTERIZATION OF BNC

3.2.1 Scanning Electron Microscopy (SEM)

Microscopic analyses of the BNC were performed after the purification processes in order to evaluate the arrangement of the nanofibers forming the BNC network through scanning electron microscopy.

The micrographs of the cellulose suggest an intertwined and aggregated structure (Figure 2) of cellulose nanofibril chains. This morphology is characteristic of BNC, as demonstrated in several studies (Pogorelova *et al*., 2020; El-Nagga *et al*., 2023). Its surface consists of bundles oriented in random directions with some surface irregularities, similar to those reported by Souza and Recouvreux (2016) when analyzing cellulose produced by bacteria.

Figure 2 - SEM micrographs of BNC at scales of
50 µm × 50 µm, 10 µm × 10 µm, 5 µm × 5 µm, and 2 µm × 2 µm, respectively.



Source: Scanning Electron Microscopy images, LAPAM - UFSM.

Cellulose nanofibrils generally exhibit a high aspect ratio (length/diameter), meaning they have a relatively long length compared to their diameter. According to studies by Souza and

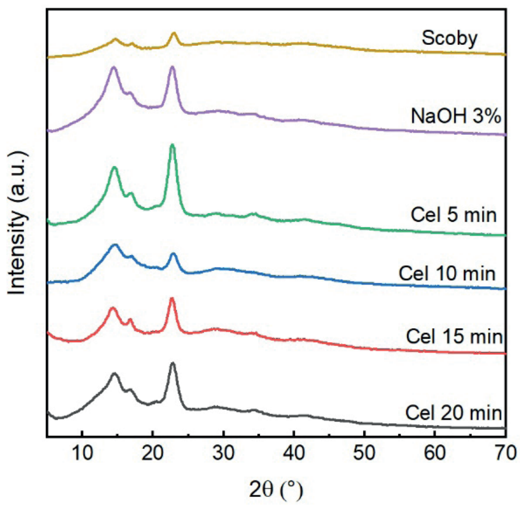
Recouvreux (2016), BNC presents an aspect ratio close to 50, which makes the cellulose nanofibrils high potential for use as reinforcement in nanomaterials. The high aspect ratio of BNC provides not only reinforcement potential but also superior mechanical properties, such as high tensile strength and elastic modulus, favoring the formation of porous and interconnected networks (Pogorelova *et al*., 2020; Wang *et al*., 2023; Da Silva Pereira *et al*., 2024).

3.2.2 X-Ray Diffraction (XRD) of BNC

Cellulose membranes were characterized by X-ray diffraction (XRD) to determine their crystallinity, identify possible crystalline structures, and verify the characteristic peaks of BNC after ultrasonic processing at different times (5, 10, 15, and 20 minutes) (Figure 3).

The diffractogram obtained from purified BNC (3% NaOH sample) showed three main diffraction peaks at 2θ = 14.7°, 16.4°, and 22.6°, corresponding to the crystallographic planes ($1\bar{1}0$), (110), and (200), respectively. These peaks confirm the typical crystalline structure of cellulose type I (Dima *et al*., 2017; Charoenrak *et al*., 2023).

Figure 3 - X-ray diffraction pattern of BNC with varying ultrasonic processing times.



Source: Author’s elaboration.

X-ray diffraction (XRD) characterization is essential to identify and confirm the crystalline structures of BNC, especially after undergoing, purification, and sonication processes. The technique confirms that bacterial cellulose exhibits the crystalline form of cellulose I. Its structure consists of highly ordered crystalline regions interspersed with amorphous zones, which can be quantified by the crystallinity index (Csóka; Ohtani, 2025). Studies have shown that BNC, even after the purification process, maintains its high degree of crystallinity (values between 62% and 81%), containing nanometric-sized crystals (12.9-25 nm), forming a dense matrix (Rezaei *et al*., 2025).

The high crystallinity and predominance of the Iα phase are directly related to its mechanical strength, thermal stability, and water absorption capacity (Mohite; Patil, 2014). These properties are crucial for biomedical applications, such as wound dressings, as they ensure structural integrity, flexibility, and durability of the cellulose-based materials. Furthermore, the nanofibrillar structure observed by scanning electron microscopy and corroborated by XRD analysis contributes to high porosity and fluid exchange capacity, facilitating adhesion to the wound bed (Csóka; Ohtani, 2025).

3.3 PHYSICOCHEMICAL CHARACTERIZATION OF THE NANOEMULSION

The nanoemulsion containing olive leaf extract presented suitable values for average droplet size, polydispersity index (PDI), zeta potential, and pH, as shown in Table 3 below.

Table 3 - Average droplet size, polydispersity index, zeta potential, and pH of the nanoemulsion containing olive leaf extract.

FORMULATION	AVERAGE SIZE (nm)	PDI	ZETA POTENTIAL (mV)	pH
Nanoemulsion containing extract	164.2 ± 7.46	0.21 ± 0.002	-18.2 ± 1.51	3.99 ± 0.09

Source: Author's elaboration.

Nanoemulsions containing plant extracts tend to exhibit favorable physicochemical and multifunctional properties, making them promising for topical applications, particularly for wound healing. Nanoemulsions are characterized by nanometric droplet sizes (18-200 nm), low polydispersity index (< 0.5), and zeta potential values around ±30 mV, parameters that indicate good physical-chemical stability (Tominc *et al*., 2024). Nanoformulations incorporating hydroalcoholic extracts rich in polyphenols, flavonoids, and other bioactive compounds can enhance antioxidant, anti-inflammatory, and antimicrobial activities (Tominc *et al*., 2024; Haładyn *et al*., 2025).

Functionally, nanoemulsions promote controlled and sustained release of bioactive compounds, significantly improving permeation and local bioavailability (Dal Mas *et al*., 2016; Romas *et al*., 2021). These features are essential for achieving an effective therapeutic effect on specific lesions, favoring hydration, modulation of the inflammatory response, and protection against bacterial infections, especially from pathogens such as *Staphylococcus aureus*, *Streptococcus pyogenes*, and *Escherichia coli* (Dal Mas *et al*., 2016; Sungpud *et al*., 2020; Tominc *et al*., 2024; Tinh *et al*., 2025).

Thus, nanoemulsions are suitable for incorporation into hydrophilic matrices such as hydrogels or nanoemulgels, while maintaining color stability, pH, and physicochemical integrity (Thungmungmee; Wisidsri, 2025). Among their most promising applications are advanced wound dressings, topical anti-inflammatory formulations, moisturizers, and antimicrobial and antioxidant products (Romas *et al*., 2021; Tominc *et al*., 2024).

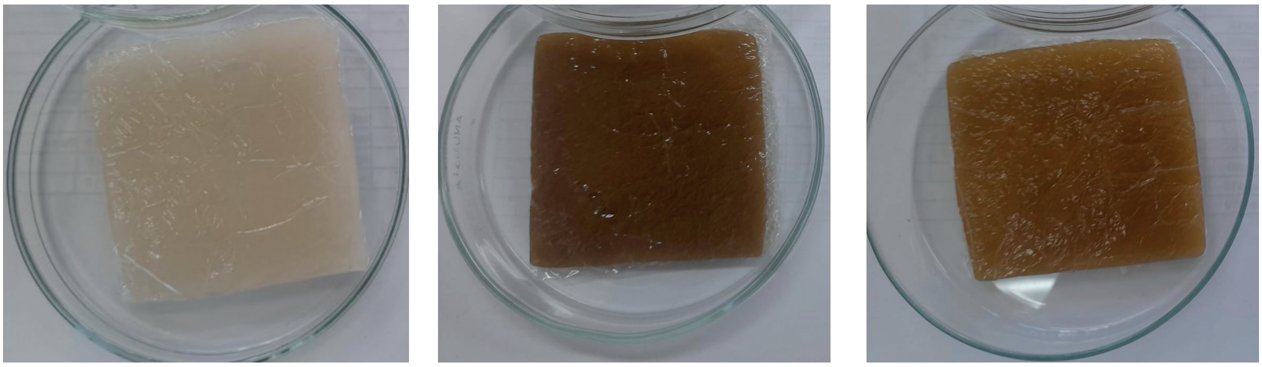
3.4 EVALUATION OF BNC-BASED HYDROGELS

The visual appearance of the hydrogels can be observed in figure 4 (a, b, and c). The pure cellulose hydrogel shows a more transparent color, resulting from the whitish tone of the bacterial cellulose used. However, the cellulose-based hydrogel containing hydroalcoholic extract displays a darker caramel color, attributed to the added extract. In contrast, the cellulose-based hydrogel containing the nanoemulsion with extract exhibits a lighter caramel color, possibly due to the extract being incorporated within a nanoemulsion.

Macroscopically, the hydrogels demonstrate excellent consistency, being highly flexible and well-hydrated, allowing them to adapt closely to the skin in the area of the wound where they are applied.

Figure 4 - a) Pure hydrogel; b) Hydrogel with extract; c) Hydrogel with nanoemulsion containing extract.

A B C



Source: Author's elaboration.

The literature describes hydrogels as three-dimensional polymeric materials with a high water-holding capacity, consisting of networks of natural or synthetic polymers capable of absorbing and retaining large amounts of water or biological fluids (Dong *et al*., 2025). This ability to retain water gives hydrogels properties that resemble the extracellular matrix (ECM) of biological tissues, providing them with softness, flexibility, and biocompatibility (Ullah; Lim, 2022; Quazi *et al*., 2025).

For biomedical applications, hydrogels are widely used because their properties can be tuned-such as porosity, mechanical strength, flexibility, adhesiveness, controlled release capacity, and responsiveness to environmental stimuli including pH, temperature, enzymes, and light (Ullah; Lim, 2022; Dong *et al*., 2025; Quazi *et al*., 2025).

The main applications of hydrogels include: 1) Tissue engineering, supporting cell growth and differentiation while promoting the regeneration of skin, cartilage, and even bone tissue (Zoller, 2025; Liu *et al*., 2025; Martinet *et al*., 2025); 2) Controlled drug delivery systems, acting as reservoirs for the sustained and localized release of drugs, proteins, and peptides (Dong *et al*., 2025); 3) Contact lenses, medical devices, and sensors, due to their transparency, biocompatibility, and ability to incorporate active compounds (Ullah; Lim, 2022; Zoller, 2025; Quazi *et al*., 2025). In summary, hydrogels represent a multifunctional and tunable alternative for biomedical applications, with special emphasis on wound dressings, advanced tissue engineering, and controlled drug delivery systems, owing to their excellent biocompatibility (Dong *et al*., 2025).

4 CONCLUSION

The results obtained in this study indicate that the production of BNC from Kombucha (scoby) residues represents a sustainable and effective alternative for obtaining a natural biopolymer with a high degree of purity and structural properties suitable for biotechnological, cosmetic, and biomedical applications. During the purification process, the adopted protocol effectively removed microbial and vegetal impurities, ensuring the integrity of the BNC matrix, as confirmed by morphological and structural analyses.

Alongside the excellent results for BNC, the nanoemulsion containing olive leaf extract showed excellent physicochemical characteristics (average particle diameter, polydispersity index, zeta potential, and pH), parameters that indicate stability and enhanced bioavailability of the extract's bioactive compounds. Thus, the nanoemulsion is suitable as a nanocarrier system for bioactive incorporation, broadening the therapeutic potential of formulations.

Finally, the hydrogels based on BNC containing free and nanoencapsulated extract demonstrated excellent consistency and moisture, properties that make them promising for topical applications, such as functional wound dressings, controlled-release systems, and dermocosmetic products aimed at skin regeneration and hydration.

Therefore, this study concludes that BNC derived from Kombucha scoby has great potential as a renewable and functional biopolymer, suitable for nanotechnological systems, while also promoting the sustainable reuse of agro-industrial residues and contributing to the development of sustainable and innovative technologies.

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