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USE OF BACTERIAL CELLULOSE AND NANOSILVER IN DRESSING MATERIALS

This work examines modern approaches to creating dressing materials for treating acute and chronic wounds using bacterial cellulose. It analyzes skin structure, main stages of wound healing, and factors that may slow or complicate regeneration. It demonstrates that traditional dressings do not always provide optimal conditions for tissue restoration, whereas hydrogel systems maintain a moist environment, ensure gas exchange, and create favorable conditions for cell proliferation. Due to their high biocompatibility, ability to absorb exudate, and easy removal without traumatizing newly formed tissue, bacterial cellulose hydrogels hold a prominent position among modern wound dressings.

The work reviews the use of natural and synthetic polymers for hydrogel materials, their advantages, and limitations. Particular attention is paid to bacterial cellulose (BC), as a promising biomaterial for tissue engineering and regenerative medicine. It highlights its unique properties, including high purity, nanofibrillar structure, biocompatibility, ability to retain significant water amounts, and creation of optimal wound healing conditions. The incorporation of bacterial cellulose has been shown to yield composite hydrogels characterized by superior mechanical performance, structural stability, and controlled release of bioactive substances.

It is noted that the lack of intrinsic antimicrobial activity in bacterial cellulose necessitates its modification. Introducing silver nanoparticles, characterized by broad-spectrum antimicrobial action and actively used in biomedical materials, is considered a promising approach. Composite hydrogels based on bacterial cellulose and silver nanoparticles combine high biocompatibility, tissue regeneration capacity, and pronounced antimicrobial activity, making them promising for modern wound dressings.

Key words: hydrogels, bacterial cellulose, wound dressings, nanoparticles, nanosilver.

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ВИКОРИСТАННЯ БАКТЕРІАЛЬНОЇ ЦЕЛЮЛОЗИ ТА НАНОСРІБЛА В ПЕРЕВ'ЯЗУВАЛЬНИХ МАТЕРІАЛАХ

У роботі розглянуто сучасні підходи до створення перев'язувальних матеріалів для лікування гострих і хронічних ран із використанням бактеріальної целюлози. Проаналізовано будову шкіри, основні етапи загоєння ран та чинники, що можуть уповільнювати або ускладнювати процес регенерації. Показано, що традиційні перев'язувальні матеріали не завжди забезпечують оптимальні умови для відновлення тканин, тоді як гідрогелеві системи здатні підтримувати вологе середовище, забезпечувати газообмін і створювати сприятливі умови для проліферації клітин. Завдяки високій біосумісності, здатності поглинати ексудат і легкому видаленню без травмування новоутвореної тканини гідрогелі з бактеріальної целюлози посідають важливе місце серед сучасних ранових покриттів.

У роботі розглянуто використання природних і синтетичних полімерів для створення гідрогелевих матеріалів, їх переваги та обмеження. Особливу увагу приділено бактеріальній целюлозі (BC), як перспективному біо-



матеріалу для тканинної інженерії та регенеративної медицини. Висвітлено її унікальні властивості, зокрема високу чистоту, нанофібрилярну структуру, біосумісність, здатність утримувати значну кількість води та створювати оптимальні умови для загоєння ран. Показано, що використання бактеріальної целюлози дозволяє отримати композитні гідрогелі з покращеними механічними характеристиками, стабільною структурою та можливістю контрольованого вивільнення біологічно активних речовин.

Зазначено, що відсутність власної антимікробної активності у бактеріальній целюлозі зумовлює необхідність її модифікації. Як перспективний підхід розглянуто введення наночастинок срібла, що характеризуються широким спектром антимікробної дії та активно застосовуються у біомедичних матеріалах. Показано, що композитні гідрогелі на основі бактеріальної целюлози та наночастинок срібла можуть поєднувати високу біосумісність, здатність до регенерації тканин і виражену антимікробну активність, що робить їх перспективними для створення сучасних ранових покриттів.

Ключові слова: гідрогелі, бактеріальна целюлоза, ранові пов'язки, наночастки, наносрібло.

Problem Statement

Modern medicine faces the challenge of effective wound treatment of various origins, including burns, chronic, and infected skin lesions [1, 2]. Traditional dressings such as gauze and bandages do not provide an optimal microenvironment for tissue regeneration, as they fail to maintain sufficient moisture, may adhere to the wound, and cause additional trauma during changes. Accordingly, interest in biocompatible hydrogel materials capable of providing conditions for wound healing is growing [3 – 7].

Bacterial cellulose is a promising biopolymer for modern wound dressings due to its high purity, nanofibrillar structure, significant water retention capacity, and biocompatibility [8 – 11]. However, its significant drawback is the lack of intrinsic antimicrobial activity, limiting its use for infected wounds. One promising solution is creating composites based on bacterial cellulose reinforced with antimicrobial agents, particularly silver nanoparticles, to impart antimicrobial properties to hydrogels. Thus, the study of novel composite materials based on bacterial cellulose with metal nanoparticles for effective wound dressings is of considerable relevance. [8].

Analysis of Recent Research and Publications

In recent years, considerable research efforts have been directed toward the development of bacterial cellulose-based hydrogel wound dressings [8]. Hydrogels have been demonstrated to sustain a hydrated wound bed, thereby stimulating cellular migration and accelerating regenerative processes. Particular attention is paid to biopolymer hydrogels based on bacterial cellulose with the addition of chitosan, hyaluronic acid, alginates, collagen, etc. [2, 8, 12 – 14].

Bacterial cellulose is considered one of the most promising materials for tissue engineering and wound dressings due to its unique physicochemical and mechanical properties. Research has shown that it can be used as a temporary skin substitute, as well as a base for controlled drug release systems. However, numerous works emphasize that pure bacterial cellulose lacks antimicrobial properties, which reduces its effectiveness in treating infected wounds [8, 14].

In this regard, many studies focus on bacterial cellulose composites with antimicrobial agents [15 – 19]. Particular attention is paid to silver, copper, and zinc oxide nanoparticles, which demonstrate pronounced antimicrobial activity against Gram-positive and Gram-negative bacteria, as well as fungi. Incorporating silver nanoparticles into bacterial cellulose structure provides prolonged antimicrobial action and improves dressing functional properties. However, optimal nanoparticle incorporation methods, their uniform distribution within the matrix, and reduction of potential toxicity remain important challenges and require further research [19].

Formulation of the Research Objective

The objective of this work is to investigate composite materials based on bacterial cellulose with antimicrobial properties, in particular silver nanoparticles, to develop effective hydrogel wound dressings with improved antimicrobial and physicochemical properties.

Presentation of the Main Research Material

The skin, the body's largest organ, serves as a vital barrier against physical and chemical factors, environmental microflora [1]. The skin consists of three main layers: the epidermis, dermis and hypodermis. The outer epidermis is predominantly composed of keratinized cells. Keratin is the main component that makes the skin waterproof and protective. The second or middle dermal layer comprises blood vessels managed by living cells. The third layer of the skin is the fatty layer, formed by subcutaneous tissue [2].

However, skin damage (wounds) can lead to serious consequences and disruption of the integrity of the entire organism [3]. During wound healing, the skin begins to heal by restoring dead and damaged tissues and cellular structures, starting from the deeper layers. Wound healing involves four key stages: hemostasis, inflammation, cell proliferation, remodeling. [4]. Wounds can also be divided into acute and chronic. Acute wounds heal within four weeks, following typical healing stages. Chronic wounds take a long time to heal, possibly exceeding four weeks. Due to complications, chronic wounds cannot follow the normal healing phases in an orderly and rapid manner [1, 2]. Examples of chronic wounds include burns, pressure injuries, infections, leg ulcers, etc. [3]. Chronic wound care imposes substantial costs, and there is a pressing need to develop affordable wound dressing materials to ensure broad accessibility.

Some notable factors affecting the wound healing process include desiccation, infection, maceration, necrosis, pressure, trauma, and edema [3, 4]. Desiccation causes dehydration and cell death. Infection indicates the presence of bacteria at the wound site, leading to the production of drainage or exudate, which may be accompanied by fever. Maceration occurs due to excessive moisture exposure at a wound site that is not kept clean and dry. Necrosis forms dead tissue that can resist wound healing. Pressure is another important factor. High pressure restricts blood flow and affects healing. Edema impairs local blood supply, leading to swelling due to excessive accumulation of fluid and leukocytes at the wound site. Traumatic wounds are defined as unplanned injuries that range in severity from minor abrasions to critical trauma, such as gunshot wounds [4]. Therefore, it is essential to select dressings for wound healing that meet all the requirements. However, many options can serve as the basis for developing a new biopolymer material with broad-spectrum antibacterial properties.

Wound dressings are available in a variety of pharmaceutical and structural forms, including hydrogels, films, nanofibrous coatings, foam materials, topical formulations, plates, sponges, and bandages [3, 5–7]. This diversity of forms reflects the need to select materials according to the wound type and healing conditions.

Hydrogel dressings are widely used due to their high biocompatibility, ability to absorb water and maintain a moist environment, and good permeability to gases and solutes [8–11]. Unlike traditional gauze, which primarily isolates the wound and promotes drying of the exudate, hydrogels actively interact with the wound surface, maintain local moisture, and stimulate regenerative processes through cellular factors and cytokines [12]. Such dressings are easily removed without damaging newly formed tissue and do not leave residues on the wound; they are also capable of retaining exudate, reducing the risk of bacterial spread during dressing changes [13]. At the same time, their use for wounds with heavy exudate is limited due to insufficient absorption capacity. Therefore, increasing their water absorption by forming porous structures and more elastic polymer networks is relevant.

Both natural and synthetic polymers are widely used in the development of modern wound dressings. The most common biopolymers include cellulose, chitosan, fibrin, elastin, dextran, alginate, collagen, and gelatin [2, 14]. Their use is determined by a combination of properties important for the healing process, including biocompatibility, lack of toxicity, biodegradability, accessibility, and low immunogenicity [4].

Polymeric materials are widely employed to produce hydrogels of both synthetic and natural origin. Traditionally, hydrogels are synthesized from organic synthetic polymers, including polyvinyl alcohol (PVA), polyacrylic acid (PAA), polyethylene glycol (PEG), poly(DL-lactide) (PLA) and other compounds. These materials exhibit sufficient mechanical strength and controllable degradation rates. Owing to biocompatibility, biodegradability, absence of cytotoxicity, as well as controllable mechanical parameters and relatively inert nature, synthetic polymers are widely utilized in the design of biomedical hydrogel systems. However, such materials do not always provide a microenvironment conducive to cellular differentiation and tissue regeneration [14].

Parallel to this, significant attention is given to natural polymers, primarily of polysaccharide nature. These include chitosan (CS), alginic acid (Alg), cellulose (CEL), hyaluronic acid (HA), dextran (Dex), chondroitin sulfate, and heparin. Additionally, protein biopolymers such as gelatin, collagen, keratin, and silk fibroin are being investigated. Such biomaterials are considered a promising basis for medical hydrogels due to their high biocompatibility and biodegradability. In recent years, the use of natural polymers in this field has increased significantly, which is explained by their wide availability, relatively low cost, lack of toxicity, and good compatibility with biological tissues [14].

Nevertheless, natural polymers have certain limitations. The main disadvantages include insufficient mechanical strength, unstable hydration rates, significant dependence of properties on environmental conditions, and potential antigenicity. These factors can significantly limit their application in medical practice without additional modification or combination with other materials [14].

When creating an effective wound dressing, a complex of functional characteristics is considered. These include hemostatic capacity, antimicrobial protection, efficient absorption of wound exudate, sterilizability, promotion of wound surface debridement, adequate gas permeability, ease of application, as well as biodegradability and the absence of toxic effects on tissues [3].

Bacterial cellulose is produced by a symbiotic culture of bacteria and yeast (SCOBY), representing a complex polymicrobial system with two interconnected parts: a dense cellulose film on the nutrient medium surface and the liquid phase beneath it [15]. The surface film predominantly comprises acetic acid bacteria of the genera *Komagataeibacter* and *Acetobacter*, whose share can reach 60–95% of the total biomass. They synthesize a three-dimensional network of cellulose nanofibrils stabilized by exopolysaccharides. High water content, up to 95%, imparts hydrogel properties to this material, ensuring structural elasticity and flexibility. These natural hydrogels formed by the microbial community have unique properties and structure. This material offers important advantages, including natural origin, a nanofibrous structure, and biodegradability [16].

Bacterial cellulose (BC) is used as a temporary skin substitute, providing coverage of the damaged area, protection against external contamination, maintenance of optimal moisture, and absorption of exudate without adherence to the wound surface [17, 18]. Due to these properties, it is also used in transdermal drug delivery systems. Despite high regenerative and healing characteristics, BC lacks antimicrobial activity, limiting its direct biomedical applications [19]. To

overcome this drawback, modified antimicrobial biomaterials based on BC are developed by integrating antibacterial agents into its structure via physical or chemical formation methods [19].

Bacterial cellulose (BC) and materials derived from it are considered promising biomaterials for tissue engineering and regenerative medicine, particularly in wound treatment. Currently, new approaches to creating effective BC-based wound dressings are being actively developed. Compared to plant cellulose, it is characterized by higher purity, significant surface area, increased wet strength, nanofibrillar structure, and good biocompatibility, making it suitable for biomedical applications [17, 19, 20]. However, several challenges hinder their large-scale industrial application, as their production technologically requires extensive cultivation areas and molds of specific dimensions. Thus, it is advisable to use it as a base combined with other polymers of natural and/or synthetic origin.

Despite the pronounced properties of bacterial cellulose hydrogels that promote wound healing and tissue regeneration, their major drawback is the lack of intrinsic antimicrobial activity, which limits the use of this material in biomedicine [19, 22]. To address this, antimicrobial composites are created by incorporating various antimicrobial agents into its nanostructure using physical or chemical modification methods [19].

A relevant direction is the integration of metal nanoparticles or their oxides to provide necessary antibacterial activity. Silver, copper, and zinc oxide nanoparticles are most commonly used, demonstrating pronounced antimicrobial effects. Silver nanoparticles are widely applied in various biomedical fields due to their strong antimicrobial properties, particularly relevant amid rising microbial antibiotic resistance. They exhibit activity against a broad spectrum of Gram-positive and Gram-negative bacteria [22]. Moreover, elemental silver is also characterized by antifungal, antibacterial, and antiviral properties.

The effectiveness of the biomedical application of silver nanoparticles largely depends on the method of their production. In particular, biological synthesis methods yield stable nanoparticles with reduced toxicity, making them more suitable for medical use. At the same time, the scope of AgNP application is not limited to their antimicrobial action. They are also used to create and improve various biomedical products. For example, silver nanoparticles are employed in drug delivery systems, as optical probes, in orthopedic materials, and in disinfectant sprays, wound dressings, catheters, and other medical devices [22].

It has been shown that changes in AgNP size, shape, and surface characteristics can affect cell membranes and intracellular structures. This enables their use in reducing microbial pathogenicity and enhancing susceptibility to pharmaceuticals [19, 22].

Scientific literature also provides data that nanosystems based on silver nanoparticles are being investigated as auxiliary nanocarriers for various anti-inflammatory, antioxidant, antimicrobial, and antitumor substances, ensuring more efficient drug delivery [8, 19].

There are two main approaches to incorporating nanoparticles into the BC hydrogel matrix: direct introduction of pre-synthesized nanoparticles and their formation directly within the material structure (*in situ*). The first method is simpler in implementation and control but often involves nanoparticle aggregation. Conversely, *in situ* synthesis is technologically more complex but achieves more uniform particle distribution in the matrix [19].

Conclusions

The skin performs essential protective functions, and its damage can lead to serious complications. The wound healing process is complex and depends on both internal physiological processes and external factors. Chronic wounds pose a particular challenge, requiring prolonged treatment; thus, developing effective and affordable dressing materials remains a relevant task in modern biomedicine.

Bacterial cellulose is a promising biomaterial due to its nanofibrillar structure, high purity, and moisture retention capacity. It can serve as a temporary wound dressing but lacks intrinsic antimicrobial activity. Combining bacterial cellulose with other natural or synthetic polymers enables hydrogels with enhanced mechanical properties and stability.

To impart antimicrobial properties, metal nanoparticles – particularly silver – are incorporated into these materials, as they exhibit a broad spectrum of antimicrobial action. Thus, composite hydrogels based on bacterial cellulose and silver nanoparticles hold significant potential for developing advanced wound dressings with high biocompatibility and antimicrobial activity.

Bibliography

1. Cohen I. K. Lessons from the history of wound healing // *Clinics in Dermatology*. 2007. Vol. 25, No. 1. P. 3–8.
2. Abdelrahman T., Newton H. Wound dressings: principles and practice // *Surgery (Oxford)*. 2011. Vol. 29, No. 10. P. 491–495.
3. Alven S., Aderibigbe B. A. Chitosan and cellulose-based hydrogels for wound management // *International Journal of Molecular Sciences*. 2020. Vol. 21, No. 24. P. 9656.
4. Verma D., Okhawilai M., Goh K. L., Thakur V. K., Senthilkumar N., Sharma M., Uyama H. Sustainable functionalized chitosan based nano-composites for wound dressings applications: A review // *Environmental Research*. 2023. Vol. 235. P. 116580.

5. Dong Y., Cui M., Qu J., Wang X., Hyung S., Barrera J., Elvassore N., Gurtner G. C. Conformable hyaluronic acid hydrogel delivers adipose-derived stem cells and promotes regeneration of burn injury // *Acta Biomaterialia*. 2020. Vol. 108. P. 56–66.
6. Shahzad A., Khan A., Afzal Z., Farooq M., Khan J., Khan G. M. Formulation development and characterization of cefazolin nanoparticles-loaded cross-linked films of sodium alginate and pectin as wound dressings // *International Journal of Biological Macromolecules*. 2019. Vol. 124. P. 255–269.
7. El-Aassar M. R., Ibrahim O. M., Fouda M. M. G., El-Beheri N. G., Agwa M. M. Wound healing of nanofiber comprising polygalacturonic/hyaluronic acid embedded silver nanoparticles: In-vitro and in-vivo studies // *Carbohydrate Polymers*. 2020. Vol. 238. P. 116175.
8. Mo M., Wu C., Chen Y. Bacterial cellulose-based superabsorbent hydrogel for wet wound dressing // *Molecules*. 2025. Vol. 30. P. 737.
9. Li J., Yu F., Chen G., Liu J., Li X.-L., Cheng B., Mo X.-M., Chen C., Pan J.-F. Moist-retaining, self-recoverable, bioadhesive, and transparent in situ forming hydrogels to accelerate wound healing // *ACS Applied Materials & Interfaces*. 2020. Vol. 12. P. 2023–2038.
10. Zhang Z., Long M., Zheng N., Deng Y., Wang Q., Osire T., Xia X. Microstructural, physicochemical properties, and interaction mechanism of hydrogel nanoparticles modified by high catalytic activity transglutaminase crosslinking // *Food Hydrocolloids*. 2024. Vol. 147. P. 109384.
11. Wang L., Zhou M., Xu T., Zhang X. Multifunctional hydrogel as wound dressing for intelligent wound monitoring // *Chemical Engineering Journal*. 2022. Vol. 433. P. 134625.
12. Wu Y., Yang Z., Li X., Li T., Zheng J., Hu M., Yu Z., Luo W., Zhang W., Zheng F. A self-assembled hydrogel dressing as multi-target therapeutics to promote wound healing // *Chemical Engineering Journal*. 2023. Vol. 477. P. 147145.
13. Raafat A. I., El-Sawy N. M., Badawy N. A., Mousa E. A., Mohamed A. M. Radiation fabrication of xanthan-based wound dressing hydrogels embedded ZnO nanoparticles: *In vitro* evaluation // *International Journal of Biological Macromolecules*. 2018. Vol. 118. P. 1892–1902.
14. Wang Sh., Wei Yu., Wang Y., Cheng Yu. Cyclodextrin regulated natural polysaccharide hydrogels for biomedical applications – a review // *Carbohydrate Polymers*. 2023. Vol. 313. P. 120760.
15. Akhlaghi S. P., Gonzalez J. S., Ünalán S., Österberg M. Tunable functionality of nanocellulose using polymer grafting // *Advances in Colloid and Interface Science*. 2021. Vol. 288. P. 102338.
16. Hobzova R., Hrib J., Sirc J., Karpushkin E., Michálek J., Janoušková O., Gatenholm P. Embedding of bacterial cellulose nanofibers within PHEMA hydrogel matrices: Tunable stiffness composites with potential for biomedical applications // *Journal of Nanomaterials*. 2018. Vol. 2018. P. 9208014.
17. Ossowicz-Rupniewska P., Rakoczy R., Nowak A., Konopacki M., Klebeko J., Świątek E., Janus E., Duchnik W., Wenelska K., Kucharski Ł. Transdermal delivery systems for ibuprofen and ibuprofen modified with amino acids alkyl esters based on bacterial cellulose // *International Journal of Molecular Sciences*. 2021. Vol. 22. P. 6252.
18. Swingler S., Gupta A., Gibson H., Kowalczyk M., Heaselgrave W., Radecka I. Recent advances and applications of bacterial cellulose in biomedicine // *Polymers*. 2021. Vol. 13. P. 412.
19. Horue M., Silva J. M., Berti I. R., Brandão L. R., Barud H. D. S., Castro G. R. Bacterial cellulose-based materials as dressings for wound healing // *Pharmaceutics*. 2023. Vol. 15, No. 2. P. 424.
20. Olteanu G., Neacșu S. M., Joița F. A., Musuc A. M., Lupu E. C., Ioniță-Mîndrican C. B., Lupuliasa D., Mititelu M. Advancements in regenerative hydrogels in skin wound treatment: A comprehensive review // *International Journal of Molecular Sciences*. 2024. Vol. 25, No. 7. P. 3849.
21. Yi X., He J., Wei X., Li H., Liu X., Cheng F. A polyphenol and ε-polylysine functionalized bacterial cellulose/PVA multifunctional hydrogel for wound healing // *International Journal of Biological Macromolecules*. 2023. Vol. 247. P. 125663.
22. Voloshyna I. M., Lastovetska L. O., Zurnadzhian A. A., Shkotova L. V. “Green” synthesis of metal nanoparticles. Application and future perspective // *Biopolymers and Cell*. 2023. Vol. 39, No. 3. P. 170–188.

References

1. Cohen I. K. (2007). Lessons from the history of wound healing. *Clinics in Dermatology*, vol. 25, no. 1, pp. 3–8. doi.org/10.1016/j.clindermatol.2006.12.004
2. Abdelrahman T., Newton H. (2011). Wound dressings: principles and practice. *Surgery (Oxford)*, vol. 29, no. 10, pp. 491–495.
3. Alven S., Aderibigbe B. A. (2020). Chitosan and cellulose-based hydrogels for wound management. *International Journal of Molecular Sciences*, vol. 21, no. 24, pp. 9656.
4. Verma D., Okhawilai M., Goh K. L., Thakur V. K., Senthilkumar N., Sharma M., Uyama H. (2023). Sustainable functionalized chitosan-based nano-composites for wound dressings applications: A review. *Environmental Research*, vol. 235, pp. 116580.

5. Dong Y., Cui M., Qu J., Wang X., Hyung S., Barrera J., Elvassore N., Gurtner G. C. (2020). Conformable hyaluronic acid hydrogel delivers adipose-derived stem cells and promotes regeneration of burn injury. *Acta Biomaterialia*, vol. 108, pp. 56–66.
6. Shahzad A., Khan A., Afzal Z., Farooq M., Khan J., Khan G. M. (2019). Formulation development and characterization of cefazolin nanoparticles-loaded cross-linked films of sodium alginate and pectin as wound dressings. *International Journal of Biological Macromolecules*, vol. 124, pp. 255–269.
7. El-Aassar M. R., Ibrahim O. M., Fouda M. M. G., El-Beheri N. G., Agwa M. M. (2020). Wound healing of nanofiber comprising polygalacturonic/hyaluronic acid embedded silver nanoparticles: In-vitro and in-vivo studies. *Carbohydrate Polymers*, vol. 238, pp. 116175.
8. Mo M., Wu C., Chen Y. (2025). Bacterial cellulose-based superabsorbent hydrogel for wet wound dressing. *Molecules*, vol. 30, pp. 737.
9. Li J., Yu F., Chen G., Liu J., Li X.-L., Cheng B., Mo X.-M., Chen C., Pan J.-F. (2020). Moist-retaining, self-recoverable, bioadhesive, and transparent in situ forming hydrogels to accelerate wound healing. *ACS Applied Materials & Interfaces*, vol. 12, pp. 2023–2038.
10. Zhang Z., Long M., Zheng N., Deng Y., Wang Q., Osire T., Xia X. (2024). Microstructural, physicochemical properties, and interaction mechanism of hydrogel nanoparticles modified by high catalytic activity transglutaminase crosslinking. *Food Hydrocolloids*, vol. 147, pp. 109384.
11. Wang L., Zhou M., Xu T., Zhang X. (2022). Multifunctional hydrogel as wound dressing for intelligent wound monitoring. *Chemical Engineering Journal*, vol. 433, pp. 134625.
12. Wu Y., Yang Z., Li X., Li T., Zheng J., Hu M., Yu Z., Luo W., Zhang W., Zheng F. et al. (2023). A self-assembled hydrogel dressing as multi-target therapeutics to promote wound healing. *Chemical Engineering Journal*, vol. 477, pp. 147145.
13. Raafat A. I., El-Sawy N. M., Badawy N. A., Mousa E. A., Mohamed A. M. (2018). Radiation fabrication of xanthan-based wound dressing hydrogels embedded ZnO nanoparticles: In vitro evaluation. *International Journal of Biological Macromolecules*, vol. 118, pp. 1892–1902.
14. Wang Sh., Wei Yu., Wang Y., Cheng Yu. (2023). Cyclodextrin regulated natural polysaccharide hydrogels for biomedical applications – a review. *Carbohydrate Polymers*, vol. 313, pp. 120760.
15. Akhlaghi S. P., Gonzalez J. S., Ünalán S., Österberg M. (2021). Tunable functionality of nanocellulose using polymer grafting. *Advances in Colloid and Interface Science*, vol. 288, pp. 102338.
16. Hobzova R., Hrib J., Sirc J., Karpushkin E., Michálek J., Janoušková O., Gatenholm P. (2018). Embedding of bacterial cellulose nanofibers within PHEMA hydrogel matrices: Tunable stiffness composites with potential for biomedical applications. *Journal of Nanomaterials*, vol. 2018, pp. 9208014.
17. Ossowicz-Rupniewska P., Rakoczy R., Nowak A., Konopacki M., Klebeko J., Świątek E., Janus E., Duchnik W., Wenelska K., Kucharski Ł. et al. (2021). Transdermal delivery systems for ibuprofen and ibuprofen modified with amino acids alkyl esters based on bacterial cellulose. *International Journal of Molecular Sciences*, vol. 22, pp. 6252.
18. Swingler S., Gupta A., Gibson H., Kowalczyk M., Heaselgrave W., Radecka I. (2021). Recent advances and applications of bacterial cellulose in biomedicine. *Polymers*, vol. 13, pp. 412.
19. Horue M., Silva J. M., Berti I. R., Brandão L. R., Barud H. D. S., Castro G. R. (2023). Bacterial cellulose-based materials as dressings for wound healing. *Pharmaceutics*, vol. 15, no. 2, pp. 424.
20. Olteanu G., Neacșu S. M., Joița F. A., Musuc A. M., Lupu E. C., Ioniță-Mîndrican C. B., Lupuliasa D., Mititelu M. (2024). Advancements in regenerative hydrogels in skin wound treatment: A comprehensive review. *International Journal of Molecular Sciences*, vol. 25, no. 7, pp. 3849.
21. Yi X., He J., Wei X., Li H., Liu X., Cheng F. (2023). A polyphenol and ε-polylysine functionalized bacterial cellulose/PVA multifunctional hydrogel for wound healing. *International Journal of Biological Macromolecules*, vol. 247, pp. 125663.
22. Voloshyna I. M., Lastovetska L. O., Zurnadzian A. A., Shkotova L. V. (2023). «Green» synthesis of metal nanoparticles. Application and future perspective. *Biopolymers and Cell*, vol. 39, no. 3, pp. 170–188.

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