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Silver Nanoparticle Impregnated Bacterial Cellulose from Oil Palm Frond Juice and Their Antimicrobial Properties

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Abstract: Palm oil frond sap (NPS), rich in fermentable sugars and essential minerals, is a renewable substrate for the production of biocompatible biomaterials. This study aims to review the utilization of of OPFJ as a culture medium for BC biosynthesis, its functionalization with silver nanoparticles (AgNPs), and the potential of the resulting composite' for wound dressing applications. The method used was a literature review by collecting the latest and most recent journals, recording and analyzing the results of the utilization of OPFJ with AgNPs. The results showed that OPFJ-based BC exhibits nanofibrillar morphology, high crystallinity, and good mechanical stability. The incorporation of AgNPs enhances antimicrobial activity against both Gram-positive and Gram-negative bacteria, providing a dual-functional dressing material. Nonetheless, limitations persist in silver release control, cytotoxicity management, and large-scale production. Future studies should focus on pretreatment optimization of OPFJ, green synthesis of AgNPs, and in vivo evaluations to ensure clinical viability.

Keywords: Antimicrobial; Bacterial cellulose; Oil palm frond juice; Silver nanoparticles

Introduction

Sustainable biomaterials remain a challenge in the chemical industry, especially biocompatible materials for wound healing. Oil palm plantations generate abundant biomass residues, notably oil palm fronds (OPF), which are often underutilized. Oil palm frond juice (OPFJ) contains high concentrations of glucose, fructose, and minerals, making it a promising low-cost medium for bacterial cellulose (BC) production (Agustira et al., 2019; Mohamad et al., 2022).

The growing demand for sustainable biomaterials in the healthcare industry has spurred research into bacterial cellulose (BC) derived from palm oil-based agro-industrial byproducts. BC is a biopolymer synthesized by acetic acid bacteria such as Acetobacter xylinum, characterized by a nanofibrillar network with excellent mechanical strength, purity, and biocompatibility, biodegradability, porous properties (Ershov et al., 2024; Mutiara et al., 2022; Santosa et al., 2022; Selamat et al., 2019; Wu et al., 2014). Bacterial cellulose can be material of any application. Given these properties, BC has gained attention in biomedical applications including wound dressings, tissue scaffolds, and hydrogel drug delivery systems (Irham et al., 2021a, 2021b; Irham, Hardiyanti, et al., 2023).

To produce a drug delivery material while providing an antibacterial effect, a combination of BC with silver nanoparticles (AgNPs) yields a composite with superior antimicrobial performance, positioning it as a next-generation bioactive wound dressing (Audtarat et al., 2022).

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Method

The method used in this research is a literature review. Sources were taken from recent journals. Journal articles related to the use of OPFJ as a material were then followed by journal articles related to bacterial cellulose, which is a good material for use as a drug delivery device. Furthermore, journal articles describing the potential of AgNPs as a good antibacterial agent were also included.

Result and Discussion

Valorization of Oil Palm Frond Juice for Bacterial Cellulose Production

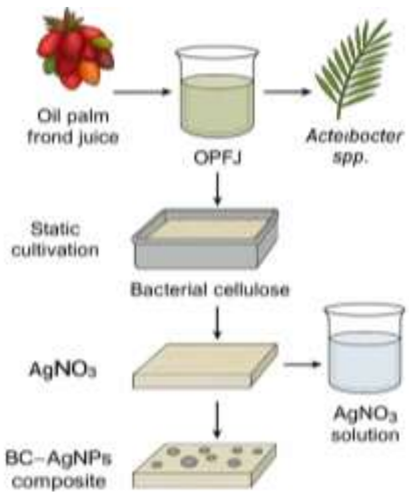

Figure 1. Schematic of BC production and AgNP

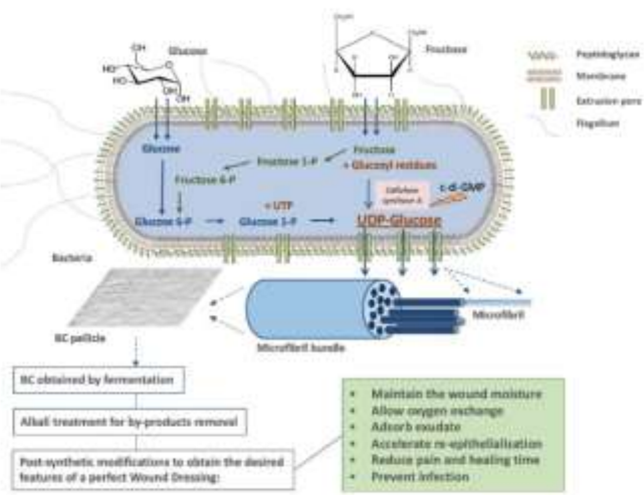

Figure 2. Schematic depiction of the steps involved in the production of a BC-based wound dressing, from the molecular mechanism of UDP-glu-cose biosynthesis in bacteria to the BC post-synthetic modifications performed, highlighting the three dimensional structure formed by the secreted chains of glucose and the features desired to be present in a wound dressing-based material (Sou Min, 2023)

The valorization of OPFJ aligns with circular bioeconomy principles by converting agricultural waste into high-value materials. Studies have reported that OPFJ contains up to 36 g/L of fermentable sugars, sufficient to support bacterial growth without additional carbon supplementation (Mohamad et al., 2022; Sou Min, 2023). However, pretreatment processes, such as lignin removal via alkaline treatment or activated carbon adsorption, can significantly improve yield and reduce fermentation inhibitors (Irham et al., 2020). Optimization of pH, temperature, and inoculum size has resulted in BC yields up to 2.3 g/L after 14 days of static fermentation (Irham, Marpongahtun, et al., 2023).

Characterization of OPFJ-Derived Bacterial Cellulose

Bacterial cellulose derived from OPFJ retains typical structural properties of conventional BC. Scanning electron microscopy (SEM) reveals nanofibrils with diameters ranging from 35 to 80 nm, forming a dense 3D network. X-ray diffraction (XRD) analysis shows crystallinity indices of 80–86%, while Fourier-transform infrared spectroscopy (FTIR) confirms the presence of characteristic cellulose Iα and Iβ polymorphs. Thermal analysis indicates decomposition temperatures above 300°C, reflecting high thermal stability (Fernandes et al., 2021; Shaaban et al., 2023; Sou Min, 2023).

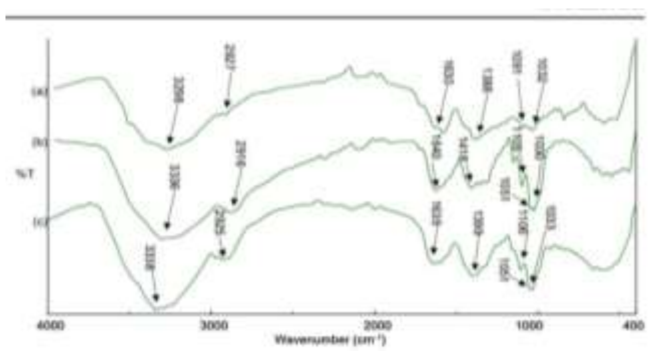

Figure 3. Fourier transform infra red analyses for a- Bacterial cel lulose, b- Silver nanoparticles, and c- Bacterial cellulose incor porated with green synthesized silver nanoparticles. Spectra were collected at wavenumber from 400 to 4000 cm−1 (Shaaban et al., 2023)

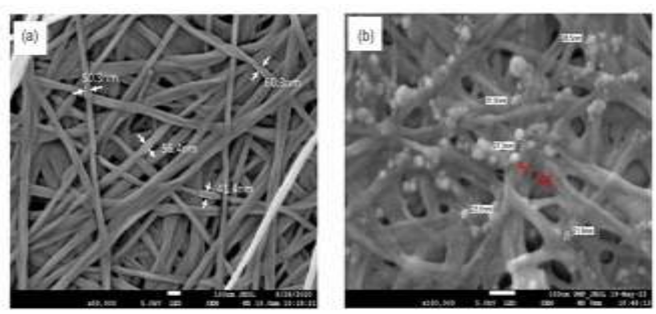

Figure 4. FESEM images of (a) pure BC, (b) BC-AgNPs

Silver Nanoparticle Functionalization of Bacterial Cellulose

Silver nanoparticle incorporation into BC can be achieved via in situ reduction or ex situ impregnation techniques (Yoon et al., 2024). The insitu method involves immersing preformed BC membranes in AgNO3 solution followed by reduction using agents such as sodium borohydride or plant extracts. Green synthesis approaches utilizing polyphenolic plant extracts minimize toxic by-products and enhance nanoparticle stability. The resulting BC–AgNP composites display uniform Ag distribution and particle diameters typically between 10 and 50 nm (Wu et al., 2014).

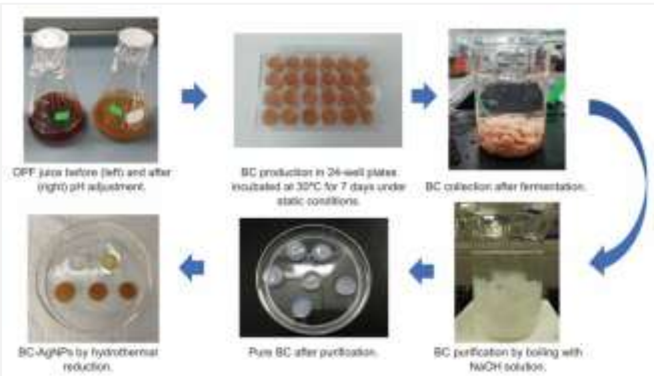

Figure 5. Scematic diagram of the development of the BC-AgNPs composite

Antimicrobial and Biomedical Properties

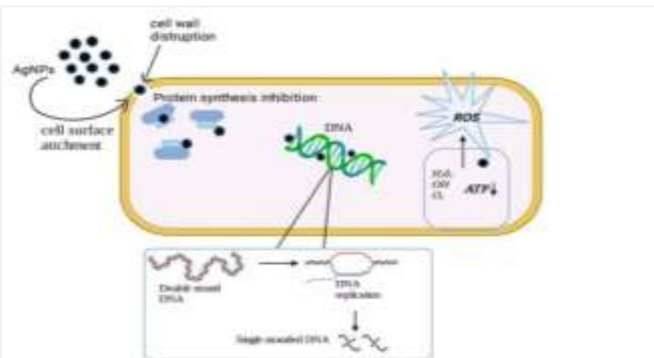

Figure 6. Mechanism action of the antibacterial activity of nanoparticle (Wu et al., 2014)

BC–AgNP composites derived from OPFJ demonstrate potent antimicrobial activity against Staphylococcus aureus and Pseudomonas aeruginosa. Inhibition zones of 25–30 mm have been reported, indicating effective bacterial suppression. Controlled silver ion release is critical to balancing antimicrobial efficacy and cytocompatibility; excessive Ag release may induce fibroblast toxicity (Ibraheem et al., 2025). In vitro cytotoxicity assays suggest that Ag concentrations below 1.5 mg/100 cm² maintain acceptable cell viability (>85%) (Charti et al., 2025). However, comprehensive in vivo evaluations remain scarce, necessitating further investigation into wound healing performance and long-term safety (Yoon et al., 2024).

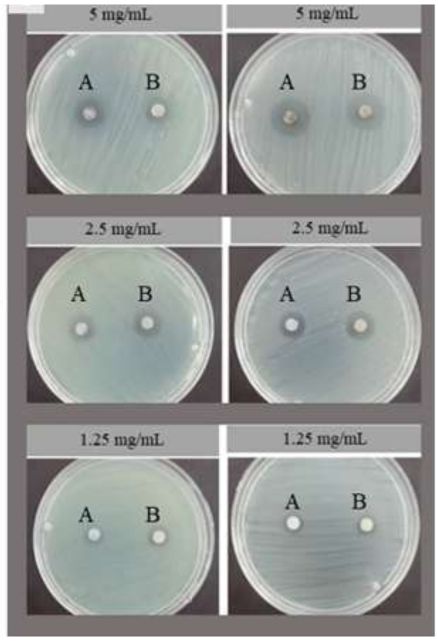

Figure 7. Antibacterial activities for these nanoparticles with different concentrations (5, 2.5, and 5 mg/mL), (a) P. aeruginosa, (b) S. aureus (Shaaban et al., 2023)

Challenges and Future Perspectives

Despite promising laboratory-scale outcomes, scaling up BC–AgNP production from OPFJ poses challenges. Variations in OPFJ composition across harvests, potential contamination, and process standardization remain critical bottlenecks (Ershov et al., 2024). Future research should integrate process control, sustainable silver sourcing, and hybrid nanocomposites with multiple bioactive agents for enhanced wound regeneration (Fahim et al., 2024). Future research should focus on developing standardized, eco-friendly production methods and evaluating the long-term biocompatibility and wound healing performance of OPFJ-derived BC–AgNP composites to realize their full potential in medical and industrial fields.

Conclusion

The valorization of oil palm frond juice (OPFJ) for bacterial cellulose (BC) production represents a sustainable and cost-effective strategy to convert agricultural residues into high-value biomaterials. OPFJ provides sufficient fermentable sugars for microbial synthesis without the need for additional carbon sources, aligning with the principles of the circular bioeconomy. The conversion of oil palm frond juice into bacterial cellulose and its subsequent functionalization with silver nanoparticles demonstrate a viable pathway for producing sustainable and high-value biomedical materials. This approach exemplifies green chemistry principles by valorizing agricultural waste into functional biopolymers. The bacterial cellulose obtained from OPFJ exhibits excellent structural, mechanical, and thermal characteristics comparable to conventional BC. Functionalization of BC with silver nanoparticles (AgNPs) enhances its antimicrobial properties, making BC–AgNP composites promising candidates for advanced biomedical applications such as wound dressings. However, challenges related to process optimization, variability in OPFJ composition, and large-scale production still need to be addressed. Further interdisciplinary studies are essential to optimize biosynthesis parameters, ensure biocompatibility, and evaluate real-world clinical efficacy.

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Author Contributions
Conceptualization, Wardatul Husna Irham; methodology, Syarifah Yusra; software, Hari Gunawan; validation, Marzuti Isra; formal analysis, Syajaratud Dur; investigation, Hari Gunawan; resources, Wardatul Husna Irham; data curation, Wardatul Husna Irham; writing—original draft preparation, Syarifah Yusra; writing—review and editing, Syajaratud Dur; visualization, Marzuti Isra; supervision, Wardatul Husna Irham; project administration, Marzuti Isra; funding acquisition, Wardatul Husna Irham. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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