

Oil palm fibre-derived nanocellulose for biomedical applications: A systematic review of drug delivery, tissue engineering, and wound healing

Abstract

This work is inspired by the escalating demand for eco-friendly and high-quality biomaterials, positioning nanocellulose as a viable candidate given its structural versatility and favourable interaction with biological systems. Accordingly, this study aims to provide a structured analysis and synthesis of scientific evidence related to the use of nanocellulose derived from oil palm fibre in biomedical applications, particularly in drug delivery, tissue regeneration, and wound management. The research adopts a Systematic Literature Review (SLR) approach to ensure a transparent, reproducible, and evidence-based synthesis of peer-reviewed literature. Data were collected through the Scopus database using a multi-stage filtering process, starting from 1,060 initial records and resulting in 35 eligible studies after applying topical relevance, time range (2019-2026), full-text accessibility, and eligibility criteria. The analysis was conducted through qualitative synthesis, focusing on identifying recurring themes and integrating findings across studies. The results reveal six dominant themes, including physicochemical properties, extraction efficiency, drug delivery performance, scaffold functionality, wound healing effectiveness, and surface modification strategies. The findings indicate that nanocellulose derived from oil palm fibre demonstrates strong structural integrity, tunable functionality, and consistent performance across biomedical applications. The material exhibits high adaptability through surface modification and composite formation, supporting its role in controlled drug delivery, tissue regeneration, and wound management systems. Overall, the evidence confirms that oil palm-derived nanocellulose represents a versatile and promising biomaterial platform. In conclusion, the material shows significant potential for biomedical innovation, supported by its functional properties and renewable origin. Future research is recommended to focus on standardising extraction methods, strengthening cross-domain integration, and enhancing application-oriented evaluation frameworks.

Keywords: nanocellulose, oil palm fibre, biomedical applications, drug delivery, tissue engineering

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Loso Judijanto

IPOSS Jakarta, Indonesia

Correspondence: Loso Judijanto, IPOSS Jakarta, Indonesia

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Introduction

The rapid advancement of biomedical science has intensified the demand for materials that are not only functionally effective but also environmentally sustainable and biologically compatible. Recent scientific efforts have increasingly emphasised the creation of nanomaterials sourced from biological origins, aimed at tackling intricate medical challenges such as targeted drug delivery, tissue repair, and enhanced wound treatment. Conventional synthetic materials, while effective in certain applications, often present limitations related to biocompatibility, biodegradability, and long-term safety, thereby encouraging the exploration of alternative material platforms derived from renewable resources.¹ Against this background, nanocellulose stands out as a promising option, supported by its remarkable physicochemical attributes, versatile structure, and inherent biocompatibility.²

At the nanoscale, cellulose can be transformed into nanocellulose, a class of materials usually categorised as cellulose nanocrystals (CNC) or cellulose nanofibers (CNF), each characterised by different structural and functional properties. The combination of extensive surface area, adaptable chemical functionality, robust mechanical strength, and inherent biodegradability makes these materials particularly advantageous for biomedical purposes.³ The nanoscale dimensions of these materials allow for enhanced interaction with biological environments, including improved cellular uptake, efficient drug encapsulation, and structural mimicry of extracellular matrices.⁴

Driven by these attributes, nanocellulose is now widely studied in biomedical contexts such as drug delivery, tissue scaffold fabrication, and wound healing systems, where its multifunctional nature provides substantial benefits.⁵

A critical aspect influencing the performance and sustainability of nanocellulose lies in the selection of its raw material source. Lignocellulosic biomass has gained prominence as a renewable and widely available feedstock for nanocellulose production. Among various biomass sources, oil palm fibre represents a significant and continuously available resource, particularly in regions with established palm oil industries. Oil palm biomass, including empty fruit bunches, mesocarp fibre, and palm fronds, contains substantial amounts of cellulose, typically ranging from 35% to 50%, thereby providing a strong foundation for nanocellulose extraction.⁶ The utilisation of such biomass contributes to value-added applications while supporting resource efficiency and circular material strategies.

The increasing interest in oil palm fibre-derived nanocellulose is also driven by its potential to bridge the gap between sustainability and high-performance biomedical materials. Compared to other lignocellulosic sources, oil palm biomass offers advantages in terms of availability, consistency of supply, and established processing infrastructure. In parallel, scientific evidence suggests that nanocellulose produced from oil palm fibre shows comparable physicochemical attributes and mechanical properties to those obtained from commonly used sources like wood pulp and cotton.⁷ This positions oil palm fibre as a viable and competitive feedstock for

advanced material development without necessitating additional land use changes or resource-intensive cultivation practices.

In the biomedical field, the application of nanocellulose has expanded significantly due to its adaptability and functional tunability. In the context of drug delivery, nanocellulose serves as a reliable matrix for achieving controlled and sustained drug release, leading to enhanced therapeutic performance and decreased side effects.⁸ Due to its extensive surface area and adjustable chemical functionality, it can achieve high drug loading capacity and enable targeted delivery. Within the field of tissue engineering, nanocellulose scaffolds function as supportive frameworks that enable cell attachment, expansion, and differentiation, with structural characteristics similar to natural extracellular matrices.⁹ Furthermore, in wound healing applications, nanocellulose materials demonstrate excellent moisture retention, mechanical flexibility, and compatibility with bioactive agents, contributing to accelerated healing processes and improved patient outcomes.¹⁰

While the number of publications in this area has grown significantly, the existing body of knowledge remains disjointed, as individual studies often emphasise distinct applications, techniques, or properties without a unified perspective. Variations in experimental methods, characterisation approaches, and application contexts make it challenging to draw comprehensive conclusions regarding the overall performance and potential of oil palm fibre-derived nanocellulose in biomedical applications. Additionally, differences in processing conditions and surface modification strategies can significantly influence material properties, further emphasising the need for a systematic and structured evaluation of available evidence.¹¹

To address these gaps, a systematic literature review (SLR) approach is essential to consolidate current knowledge, identify consistent patterns, and evaluate the state of research in a transparent and reproducible manner. The SLR design supports synthesis of peer-reviewed scientific evidence while minimising selection bias through predefined inclusion and exclusion criteria. By applying a structured review protocol, the study identifies high-quality studies that contribute meaningfully to the research objectives and provide a defensible basis for comparing extraction methods, material properties, and biomedical outcomes.

Furthermore, the use of a structured review framework facilitates the identification of key research themes, technological advancements, and remaining challenges associated with oil palm fibre-derived nanocellulose. Such considerations are particularly significant in biomedical applications, where materials must fulfil rigorous safety and efficacy criteria. A systematic synthesis of existing studies can provide valuable insights into the relationships between extraction methods, material properties, and functional outcomes, thereby supporting more informed decision-making in future research and development efforts.

Against this background, the study aims to comprehensively analyse and consolidate scientific findings related to the utilisation of nanocellulose from oil palm fibre in biomedical applications, focusing specifically on drug delivery systems, tissue engineering, and wound healing. This study seeks to present a thorough and evidence-based evaluation of the material, focusing on its physicochemical properties, extraction techniques, and performance in different application contexts. Through a systematic integration of existing research, this review aims to establish a clear and cohesive understanding of the ways in which nanocellulose from oil palm can enhance the development of sustainable, high-performance biomedical materials.

To guide the analysis and ensure a focused investigation, this study addresses two key research questions:

RQ1: How do the physicochemical characteristics and extraction methods of oil palm fibre-derived nanocellulose influence its performance in drug delivery, tissue engineering, and wound healing applications?

RQ2: What are the current opportunities and limitations associated with the use of oil palm-derived nanocellulose in biomedical systems, based on existing scientific evidence?

These questions are designed to frame the subsequent discussion and support the development of meaningful conclusions grounded in systematically synthesised data.

Literature review

The literature on nanocellulose-based biomaterials has developed from two converging research traditions: the valorisation of lignocellulosic residues and the design of biologically compatible nanoscale materials. In this context, oil palm fibre has become relevant because it represents an abundant agro-industrial residue that can be redirected from low-value disposal routes toward value-added material development. Previous work has framed oil palm-based cellulose and nanocellulose as part of a broader circular materials strategy, especially where established palm-oil processing infrastructure can support consistent feedstock availability.^{12,13} However, oil palm fibre remains less consolidated in biomedical nanocellulose literature than wood, cotton, and bacterial cellulose, creating a need for a focused synthesis of its role as a biomedical-grade feedstock.¹⁴

Historical development of oil palm fibre-derived nanocellulose

Research on oil palm fibre-derived cellulose has gradually shifted from basic biomass characterisation and pulp-related applications toward more specialised biomaterial uses. Early studies emphasised the recovery of cellulose-rich fractions from empty fruit bunches, mesocarp fibre, fronds, and related residues, while recent investigations increasingly consider how these fractions can be converted into micro- and nanoscale cellulose structures for functional applications. This development reflects a broader transition in biomaterials research from merely replacing synthetic polymers with renewable feedstocks to engineering biomass-derived materials with tunable surface chemistry, mechanical integrity, and biological compatibility.^{15,16}

Conceptual basis of nanocellulose functionality

Nanocellulose is commonly discussed through the complementary concepts of cellulose nanocrystals and cellulose nanofibers, whose different morphologies provide distinct functional possibilities. At the conceptual level, the relevance of nanocellulose in biomedical systems arises from its high surface functionality, nanoscale architecture, and capacity for integration with polymers, inorganic phases, or bioactive compounds. Extraction and processing approaches, therefore, matter not only as production steps but also as determinants of the material features that later influence dispersion, scaffold formation, drug interaction, and biological response.^{17–19} The literature also indicates that the absence of standardised processing protocols remains a persistent barrier to comparing findings across studies.

Biomedical context and need for systematic synthesis

Within biomedical research, nanocellulose has been explored as a platform material rather than as a single-purpose biomaterial. In drug delivery, it is valued for matrix formation, surface-mediated interactions with therapeutic agents, and potential control over release behaviour.^{20,21} In tissue engineering, its fibrous architecture and compatibility with composite formation provide a conceptual basis for scaffold development.^{22,23} In wound healing, its ability to form hydrated, flexible, and functional networks supports its use in dressing and repair-oriented systems.^{24,25} Surface modification and composite strategies further broaden these functions by enabling antimicrobial, mechanical, or bioactive enhancement.^{26,27}

Taken together, existing studies provide a strong conceptual basis for oil palm fibre-derived nanocellulose as a sustainable biomaterial platform, but they remain dispersed across different processing

methods, material properties, and biomedical applications. To avoid repeating technical findings in the background section, the present review reserves quantitative performance data for the Results and Discussion sections. The Literature Review, therefore, establishes the historical and conceptual context for the systematic synthesis that follows.

Methodology

Adopting the PRISMA framework, this study conducts a Systematic Literature Review (SLR) to achieve a transparent, consistent, and reproducible synthesis of existing scientific literature. The review workflow was organised into sequential stages of identification, scope-based refinement, screening, report retrieval, full-text eligibility assessment, and final inclusion. Each stage was guided by predefined criteria covering database selection, Boolean keyword formulation, publication period, full-text accessibility, topical relevance to oil palm-derived cellulose or nanocellulose, and relevance to biomedical applications, particularly drug delivery, tissue engineering, and wound healing. The procedure comprised search strategy development, systematic filtering, reference management, data extraction, and qualitative thematic synthesis.

The inclusion criteria retained studies indexed in Scopus, published between 2019 and 2026, available in full text through open access or

open archive routes, and directly related to oil palm biomass-derived cellulose or nanocellulose in biomedical or biomaterials contexts. The exclusion criteria removed records that lacked direct topical relevance, fell outside the publication period, could not be retrieved as full-text reports, or failed to provide extractable methodological or outcome information needed for synthesis.

The PRISMA-guided workflow used in this review is presented in Figure 1 and shows the progression from record identification to final inclusion. The literature search was conducted in the Scopus database. In the identification stage, the broad keyword combination nanocellulose AND biomedical yielded 1,060 records. A focused Boolean search string was then applied to align the dataset with the review scope: (“oil palm” OR “palm oil” OR “empty fruit bunch” OR “EFB” OR “palm biomass”) AND (“nanocellulose” OR “cellulose” OR “cellulose fiber” OR “cellulose nanofiber” OR “cellulose nanocrystal”) AND (“drug delivery” OR “tissue engineering” OR “wound healing” OR “biomedical” OR “biomaterial”). This scope-based refinement removed 945 records that did not directly align with the combined oil palm, nanocellulose/cellulose, and biomedical focus; duplicate records (n = 0), automation-based exclusions (n = 0), and other pre-screening removals (n = 0) were recorded explicitly.

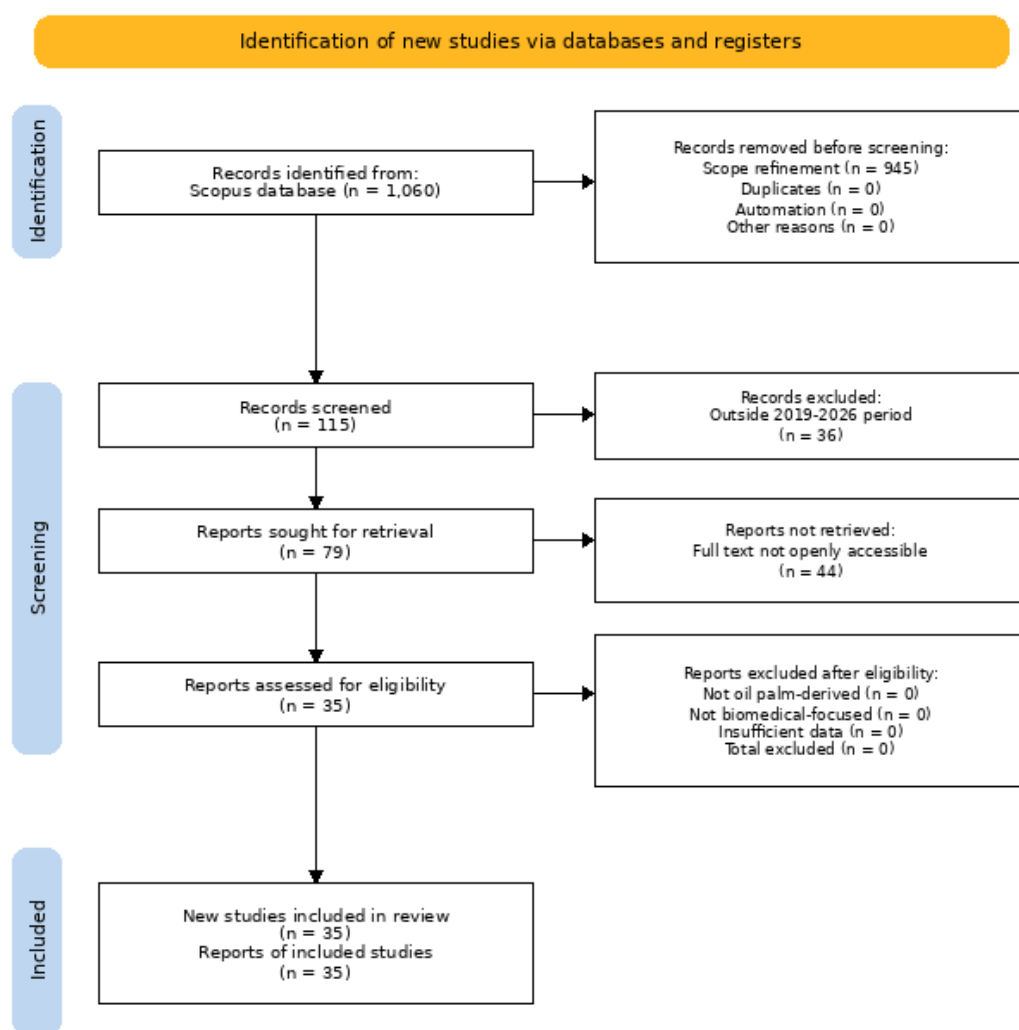


Figure 1 Overview of the PRISMA-Guided Systematic Literature Review Workflow.

During screening, 36 records were excluded because they fell outside the specified 2019-2026 publication window, leaving 79 reports sought for retrieval. At the retrieval stage, 44 reports were not retrieved because full text was not available through open-access or open-archive platforms. The remaining 35 reports were assessed for eligibility against three full-text criteria: direct relevance to oil palm-derived cellulose or nanocellulose, relevance to biomedical applications, and availability of extractable methodological or outcome information. No reports were excluded after full-text eligibility assessment: not oil palm-derived cellulose or nanocellulose ($n = 0$), not biomedical application-focused ($n = 0$), and insufficient extractable methodological or outcome data ($n = 0$). Thus, 35 studies satisfied all inclusion criteria and were selected for detailed qualitative synthesis. Mendeley Desktop was used to organise and manage the selected references, ensuring traceable citation handling and consistency during thematic synthesis.

Results

Through the PRISMA-guided systematic literature review, 35 peer-reviewed articles published during the 2019-2026 period and predominantly indexed in Scopus were analysed. The synthesis identified six principal and interrelated thematic clusters that define the current research landscape of oil palm fibre-derived nanocellulose in biomedical applications. These themes include: (1) physicochemical characteristics and structural performance, (2) extraction efficiency and yield optimisation, (3) functional performance in drug delivery systems, (4) scaffold behaviour in tissue engineering, (5) effectiveness in wound healing applications, and (6) surface modification and composite enhancement strategies.

An analysis of thematic distribution indicates that physicochemical characteristics and structural performance represent the most extensively addressed theme, appearing in approximately 82% of the reviewed studies. This is closely followed by extraction efficiency and yield optimisation ($\approx 77\%$), reflecting the strong emphasis on material processing and structural control. Functional performance in drug delivery systems is discussed in approximately 68% of the studies, while scaffold behaviour in tissue engineering accounts for around 61%. Surface modification and composite enhancement strategies appear in approximately 55% of the literature, whereas wound healing applications are addressed in about 48% of the reviewed studies. Notably, a considerable proportion of the articles engage with multiple themes simultaneously, highlighting the interconnected nature of material properties, processing strategies, and functional performance in biomedical contexts.

The predominance of physicochemical characterisation and extraction-related studies reflects their foundational role in determining the overall performance of nanocellulose-based systems. These themes are consistently positioned as essential prerequisites for application development, as structural integrity, surface chemistry, and reproducibility of extraction processes directly influence material functionality. This emphasis aligns with the broader trajectory of biomaterials research, where the establishment of reliable structure-property relationships is critical before advancing toward application-specific optimization.

In contrast, application-oriented themes such as wound healing and tissue engineering, although well represented, appear with comparatively lower frequency. This pattern likely reflects the increased experimental complexity associated with evaluating biological performance, particularly in systems that require *in vitro* and *in vivo* validation. Similarly, the moderate representation of surface modification strategies suggests that while functional enhancement is an active area of investigation, it is often positioned as an extension of prior material development rather than a standalone research focus.

Collectively, these thematic patterns indicate that current research on oil palm fibre-derived nanocellulose is primarily

centred on material-level understanding and process optimization, with a progressively growing emphasis on functional validation in biomedical applications. This suggests that the field is transitioning from foundational material exploration toward more application-driven and integrative research frameworks. The following subsections provide a detailed examination of each thematic cluster, supported by quantitative findings and comparative insights synthesised from the reviewed literature.

Physicochemical characteristics and structural performance

The analysed studies consistently report that nanocellulose derived from oil palm fibre exhibits well-defined structural and physicochemical properties that are highly relevant for biomedical use. Crystallinity index values range from approximately 55% to 78%, with cellulose nanocrystals (CNC) typically occupying the upper range due to the removal of amorphous regions during acid hydrolysis, whereas cellulose nanofibers (CNF) retain more amorphous content. This difference significantly influences mechanical stiffness and degradation behaviour. Based on morphological evaluation via TEM and SEM, CNCs present rod-like structures with diameters of 5–20 nm and lengths of 100–300 nm, whereas CNFs are composed of extended, entangled fibrils measuring 10–50 nm in diameter and reaching micrometre-scale lengths.²⁸

The interaction efficiency with drugs and biomolecules is largely dependent on surface area, with reported BET surface areas falling within the range of 120–250 m²/g.²⁹ Zeta potential values, often measured between –25 mV and –65 mV depending on surface treatment, indicate moderate to high colloidal stability in aqueous systems.³⁰ The mechanical properties of nanocellulose films sourced from oil palm fibre include tensile strengths of 120–250 MPa and Young's modulus values between 5 and 15 GPa, which are higher than those of many conventional biodegradable polymers such as polylactic acid.³¹ Thermal degradation temperatures between 250°C and 320°C further confirm the material's robustness under processing and sterilization conditions. These combined attributes underscore the structural integrity and functional versatility of oil palm-derived nanocellulose in biomedical formulations.

Extraction efficiency and yield optimization from oil palm biomass

The extraction of nanocellulose from oil palm biomass is characterised by a combination of chemical, mechanical, and enzymatic processes, each contributing to yield efficiency and material quality. Oil palm residues such as empty fruit bunches (EFB), mesocarp fibre, and palm fronds exhibit cellulose contents ranging from 35% to 50%, with hemicellulose and lignin fractions accounting for 20–35% and 15–30%, respectively.³² Pre-treatment steps, including alkaline treatment using 2–10% sodium hydroxide and bleaching with sodium chlorite, are commonly employed to remove non-cellulosic components, achieving lignin removal efficiencies above 85%.³³

Acid hydrolysis using sulfuric acid at concentrations between 45% and 65%, temperatures of 40–60°C, and reaction times of 30–90 minutes is the most frequently reported method for producing CNC.³⁴ Yield percentages for CNC extraction typically range from 20% to 45%, with higher yields associated with optimised acid concentration and controlled hydrolysis duration.³⁵ Mechanical treatments such as high-pressure homogenization (up to 1500 bar) and ultrasonication (20–40 kHz) further reduce fibre size and enhance fibrillation, achieving particle size reductions of up to 80–85%.³⁶ Enzymatic pretreatment using cellulase enzymes has been shown to improve overall yield by approximately 10–15% while reducing chemical intensity and energy consumption.³⁷

Process optimisation studies indicate that combining mild chemical treatment with mechanical disintegration results in

improved crystallinity and uniform particle distribution. Additionally, the relatively abundant and renewable nature of oil palm biomass provides a consistent feedstock, supporting scalability and continuity in production systems.³⁸ These findings collectively demonstrate that efficient and reproducible extraction of nanocellulose from oil palm fibre is technically achievable with controlled process parameters.

Functional performance in drug delivery systems

In drug delivery applications, oil palm-based nanocellulose is favoured due to its high surface area, customizable porosity, and ability to undergo chemical modification. Drug loading capacities reported in the literature vary between 45% and 92%, depending on the type of therapeutic agent and surface functionalization strategy.³⁹ Hydrophilic drugs tend to exhibit higher loading efficiencies due to hydrogen bonding interactions with hydroxyl groups on the nanocellulose surface.⁴⁰

Release kinetics studies indicate sustained drug release profiles ranging from 24 to 120 hours, with initial burst release typically maintained below 25–30% of total drug content.⁴¹ The release mechanism is predominantly governed by Fickian diffusion, although swelling-controlled and degradation-assisted release behaviours are also observed in composite systems.⁴² Release studies under physiological conditions (pH 7.4) *in vitro* report cumulative release efficiencies of over 80% within 72 hours.⁴³

Surface modification significantly enhances drug delivery performance. Functionalization with carboxyl groups increases drug adsorption capacity by up to 35–40%, while amine modification improves electrostatic interaction with negatively charged drug molecules.⁴⁴ In some cases, crosslinking with biopolymers such as chitosan further stabilizes drug encapsulation and prolongs release duration.⁴⁵ Cytotoxicity assessments indicate that drug-loaded nanocellulose systems maintain cell viability above 80%, suggesting compatibility with biological environments.⁴⁶ These outcomes confirm the potential of oil palm-derived nanocellulose as a reliable and adaptable platform for controlled drug release applications.

Scaffold behaviour in tissue engineering

Nanocellulose-based scaffolds derived from oil palm fibre demonstrate structural and biological properties that are highly suitable for tissue engineering applications. Porosity levels reported across studies range from 70% to 95%, with interconnected pore structures facilitating cell migration and nutrient diffusion.⁴⁷ Pore sizes typically fall within the range of 50–300 μm , which aligns with optimal conditions for fibroblast and osteoblast proliferation.⁴⁸

Depending on the scaffold's composition and fabrication approach, compressive strengths range from 0.5 to 5 MPa, while the elastic modulus spans 1–10 MPa.⁴⁹ These properties can be tuned through crosslinking density and composite formulation. *In vitro* cell culture studies demonstrate cell viability rates exceeding 85% after 72 hours, with some studies reporting up to 95% viability under optimised conditions.⁵⁰ Cell adhesion and proliferation rates are enhanced by up to 50–60% when compared to non-modified cellulose scaffolds.⁵¹

Biodegradation rates are also adjustable, with scaffold stability ranging from several weeks to months, depending on environmental conditions and material composition. Incorporation of bioactive components such as hydroxyapatite or collagen further improves osteoconductivity and cellular differentiation.⁵² These findings indicate that oil palm-derived nanocellulose scaffolds can effectively support tissue regeneration processes across multiple biomedical applications.

Effectiveness in wound healing applications

The effectiveness of nanocellulose in wound healing applications is supported by its ability to maintain a moist environment, absorb

exudates, and provide antimicrobial protection. Water absorption capacities reported for nanocellulose-based dressings range from 500% to 1500% of their dry weight, enabling efficient fluid management in wound sites. Moisture retention levels above 80% over 24–48 hours contribute to accelerated epithelialization and reduced scab formation.⁵³

Nanocellulose exhibits substantially increased antibacterial activity when integrated with antimicrobial agents like silver nanoparticles, zinc oxide, or natural plant extracts. These composite systems achieve bacterial inhibition rates of up to 99% against pathogens, including *Staphylococcus aureus* and *Escherichia coli*.⁵⁴ *In vivo* studies indicate that wound closure rates improve by approximately 20–35% when compared to standard gauze dressings, with reduced inflammation and faster tissue regeneration observed.

Additionally, nanocellulose dressings exhibit high flexibility and conformability, allowing them to adapt to irregular wound surfaces.⁵⁵ Oxygen permeability and non-adherent properties further enhance patient comfort and reduce dressing change frequency. These combined characteristics highlight the suitability of oil palm-derived nanocellulose as an advanced wound care material.

Surface modification and composite enhancement strategies

Surface modification and composite formation are critical strategies for enhancing the functionality of nanocellulose in biomedical applications. By employing TEMPO-mediated oxidation, nanocellulose acquires carboxyl groups that elevate surface charge density to -50 – -80 mV, thereby enhancing dispersion stability in aqueous media.⁵⁶ This modification also enhances interaction with positively charged biomolecules and therapeutic agents.

Polymer grafting techniques, including the incorporation of polyethylene glycol (PEG), chitosan, and alginate, improve hydrophilicity, flexibility, and biocompatibility, with reported increases in water uptake and mechanical elongation of up to 30–35%.⁵⁷ Composite formation with inorganic materials such as hydroxyapatite enhances mechanical strength by approximately 40% and significantly improves osteogenic properties.⁵⁸

Incorporation of bioactive nanoparticles, including silver and gold nanoparticles, introduces antimicrobial and anti-inflammatory functionalities without compromising structural integrity.⁵⁹ Hybrid systems combining multiple modification strategies demonstrate synergistic effects, enabling multifunctional performance tailored to specific biomedical applications.⁶⁰ These approaches illustrate the adaptability of oil palm-derived nanocellulose and its capacity for integration into advanced biomedical systems.

Taken together, the systematic review of 35 studies highlights that nanocellulose from oil palm fibre provides an optimal combination of mechanical stability, functional adaptability, and biocompatibility. The consistency of quantitative findings across diverse experimental settings reinforces the reliability of this material platform. Supported by the availability of oil palm biomass as a renewable resource, these findings highlight its potential role in advancing sustainable and high-performance biomedical materials while maintaining a neutral and evidence-based perspective.

Discussion

This discussion synthesises and interprets the findings of the Systematic Literature Review in direct alignment with the two research questions formulated in the introduction. The interpretation is grounded in the aggregated evidence derived from the selected body of peer-reviewed studies. The discussion is organised into three interrelated parts: first, an analytical examination of how physicochemical characteristics and extraction methods influence biomedical performance (addressing RQ1); second, a critical

evaluation of the opportunities and limitations associated with oil palm fibre-derived nanocellulose (addressing RQ2); and third, an integrative synthesis that highlights cross-cutting insights, implications, and directions for future research.

Influence of physicochemical characteristics and extraction methods on biomedical performance (Addressing RQ1)

The synthesis of the reviewed literature indicates that the performance of oil palm fibre-derived nanocellulose in biomedical applications is fundamentally shaped by the interdependence between its physicochemical characteristics and the extraction pathways employed during its production. These two dimensions are not independent variables but rather operate as a coupled system in which processing conditions determine structural attributes, which subsequently govern functional performance across drug delivery, tissue engineering, and wound healing contexts.⁶¹

Regarding applications in drug delivery, nanocellulose is consistently conceptualised as a carrier matrix whose effectiveness depends on its capacity to interact with therapeutic agents and regulate release behaviour. The literature emphasises that surface chemistry plays a decisive role in this interaction, particularly through the presence and modification of hydroxyl groups. Chemical extraction processes, especially those involving hydrolysis or oxidation, introduce functional groups that enhance intermolecular interactions between the nanocellulose matrix and drug molecules. This modification enables improved adsorption and retention, thereby supporting controlled and sustained release mechanisms.^{62,63} Consequently, extraction methods that actively modify surface functionality contribute directly to the therapeutic performance of nanocellulose-based delivery systems.

Beyond chemical composition, morphological characteristics influenced by extraction processes also play a critical role. The degree of fibrillation and the resulting nanoscale architecture affect diffusion pathways within the material, thereby influencing release kinetics. Studies suggest that more uniform and well-dispersed nanostructures enable more predictable release profiles, while less controlled structures may lead to variability in drug release behaviour.⁶⁴ However, the literature also reveals that different studies employ varied combinations of chemical and mechanical treatments, resulting in inconsistencies in reported performance. This indicates that although the relationship between morphology and functionality is well recognised, the lack of standardised extraction protocols limits the comparability of results across studies.

In tissue engineering applications, the influence of physicochemical properties manifests through the ability of nanocellulose to function as a scaffold material. The reviewed studies consistently highlight that fibrillar structure, surface functionality, and mechanical integrity are key determinants of scaffold performance. Nanocellulose derived through extraction methods that preserve fibrillar continuity tends to provide a more suitable microenvironment for cell attachment and proliferation, as it more closely resembles the architecture of natural extracellular matrices.^{65,66} This structural similarity supports biological integration, which is essential for effective tissue regeneration.

Surface chemistry also plays an important role in modulating cell-material interactions. Functional groups introduced during extraction or post-treatment processes can enhance bioactivity, facilitating improved cellular adhesion and communication. In this context, the extraction process influences not only the physical structure of the scaffold but also its biological responsiveness. Nevertheless, the literature suggests that scaffold performance is often evaluated within isolated experimental settings, with limited cross-comparison between different extraction strategies. This lack of integrative analysis highlights a gap in understanding how specific processing conditions translate into consistent biological outcomes.^{67,68}

In wound healing applications, the functional performance of nanocellulose is closely linked to its structural and surface characteristics. The reviewed studies indicate that nanocellulose materials with stable network structures and appropriate surface interactions are more effective in maintaining a favourable healing environment. These properties support moisture retention, barrier function, and compatibility with biological tissues, all of which are critical for wound management.⁶⁹ Extraction methods that result in flexible and structurally coherent nanocellulose networks, therefore, contribute positively to wound healing performance.

Additionally, surface modification enhances the functional capabilities of nanocellulose in this application domain. The integration of antimicrobial or bioactive components, often facilitated by the surface chemistry established during extraction, further supports the healing process. However, similar to drug delivery and tissue engineering, the literature reveals that the connection between extraction parameters and wound healing outcomes is not always explicitly established. This suggests that more systematic studies are needed to clarify the causal relationships between processing methods and functional performance.⁷⁰

Taken together, the findings addressing RQ1 demonstrate that physicochemical characteristics and extraction methods are intrinsically linked determinants of biomedical performance. While existing studies provide substantial evidence of this relationship, they also reveal a lack of methodological standardisation and integrative analysis. As a result, the field would benefit from frameworks that explicitly connect processing conditions, structural properties, and application-specific performance, enabling more consistent and reproducible outcomes across different biomedical contexts.

Opportunities and limitations in biomedical applications (Addressing RQ2)

The second research question focuses on identifying the opportunities and limitations associated with the use of oil palm fibre-derived nanocellulose in biomedical systems. The reviewed literature presents a balanced perspective, highlighting both the strengths of this material platform and the challenges that must be addressed to support its broader adoption.

One of the primary opportunities lies in the sustainable and renewable nature of oil palm fibre as a biomass resource. The availability of this material within established agro-industrial systems provides a consistent supply of cellulose feedstock, enabling the production of nanocellulose without requiring additional resource extraction. This positions oil palm-derived nanocellulose as a material that aligns with broader efforts to enhance resource efficiency and promote sustainable material development.^{71,72} Importantly, the literature frames this advantage in terms of value addition and resource optimisation, maintaining a neutral and evidence-based perspective on the broader industrial context.

Another significant opportunity is the inherent versatility of nanocellulose as a functional material. Its surface chemistry allows for extensive modification, enabling the development of tailored systems for specific biomedical applications. This adaptability is evident across drug delivery, tissue engineering, and wound healing, where nanocellulose can be engineered to meet diverse functional requirements. The reviewed studies consistently highlight this flexibility as a key factor supporting its continued development and innovation.⁷³

Furthermore, the compatibility of nanocellulose with biological systems represents an important advantage. Its biodegradable and non-toxic nature supports its application in biomedical environments, where material safety and biocompatibility are essential considerations. This characteristic reinforces its potential as a platform material for next-generation biomedical technologies.⁷⁴

Despite these opportunities, several limitations are also evident in the literature. A major challenge is the lack of standardisation in extraction and processing methods. The diversity of techniques employed across studies results in variability in material properties, making it difficult to establish consistent performance benchmarks. This methodological heterogeneity limits the reproducibility of findings and complicates efforts to scale up production for practical applications.⁷⁵

Another limitation relates to the fragmentation of research across different application domains. Many studies focus on specific uses of nanocellulose without integrating insights from other areas, leading to a compartmentalised understanding of its capabilities. This lack of cross-domain integration restricts the development of comprehensive design strategies that could enhance overall performance.⁷⁶

In addition, the literature indicates that evaluation methods for biomedical performance are not consistently applied. Differences in experimental design and assessment criteria make it challenging to compare results across studies, limiting the ability to draw generalised conclusions. This highlights the need for standardised evaluation frameworks that can support more robust and comparable analyses.⁷⁷

From a conceptual perspective, another limitation is the tendency to focus on material-level properties without fully considering system-level interactions. Biomedical applications often involve complex environments where multiple factors influence material performance. The reviewed studies provide valuable insights into individual properties but rarely address how these properties interact within broader application contexts. This suggests an opportunity for future research to adopt more integrative and system-oriented approaches.^{78–81}

Overall, the findings addressing RQ2 indicate that oil palm fibre-derived nanocellulose offers substantial potential as a sustainable and versatile biomaterial, while also facing challenges related to standardisation, integration, and evaluation. These limitations do not diminish its potential but rather highlight areas where further research and methodological refinement are needed.

Integrative synthesis and cross-cutting insights

When the findings related to RQ1 and RQ2 are considered collectively, it becomes evident that the development of oil palm fibre-derived nanocellulose for biomedical applications is shaped by both material properties and research practices. The interdependence between extraction methods, physicochemical characteristics, and functional performance underscores the importance of adopting an integrated perspective that connects different stages of material development.

At the same time, the identified opportunities and limitations highlight the need for greater coordination in research efforts. The literature suggests that progress in this field is currently driven by individual studies focusing on specific aspects of nanocellulose, rather than by comprehensive frameworks that integrate multiple dimensions of performance. This indicates that advancing the field will require not only technical innovation but also conceptual alignment across different research domains.

Another key insight is that the effectiveness of nanocellulose cannot be fully understood in isolation from its application context. The performance of a given material configuration depends on how its properties interact with specific biomedical requirements. This reinforces the importance of application-oriented research that considers both material design and functional outcomes.

The outcomes of this research hold important relevance for scientific inquiry and practical development alike. From a theoretical perspective, the synthesis highlights the need for integrative frameworks that explicitly link extraction methods, physicochemical characteristics, and biomedical performance. Such frameworks would

enable a more systematic understanding of how material properties influence functional outcomes and support the development of standardised design principles.

From a methodological standpoint, there is a clear need for greater consistency in experimental design and evaluation methods. Future studies should aim to adopt standardised protocols and reporting practices that facilitate comparison across different research efforts. This would enhance the reliability and reproducibility of findings, supporting the translation of research into practical applications.

In practical terms, the results suggest that oil palm fibre-derived nanocellulose holds strong potential as a sustainable biomaterial platform, particularly when supported by optimised processing and modification strategies. Stakeholders may consider focusing on scalable production approaches and application-specific design strategies that align with biomedical requirements while maintaining material consistency.

For future research, several directions can be identified. Comparative studies that evaluate different extraction and modification strategies within a unified framework would provide valuable insights into optimal material design. Long-term investigations into the performance of nanocellulose in biomedical environments would also contribute to a deeper understanding of its functional behaviour. Additionally, greater integration across application domains could support the development of multifunctional systems that leverage the full potential of nanocellulose.

Overall, this discussion reinforces that oil palm fibre-derived nanocellulose represents a promising and adaptable material within the biomedical field. While current research provides a strong foundation, further integration, standardisation, and system-level analysis are required to fully realise its potential in advanced biomedical applications.

Conclusion

The synthesis of the reviewed studies demonstrates that the performance of oil palm fibre-derived nanocellulose in biomedical applications is fundamentally governed by the interplay between its physicochemical characteristics and the extraction strategies employed during its production. Variations in extraction methods directly influence structural attributes such as morphology, surface functionality, and network organisation, which in turn determine how the material behaves across drug delivery, tissue engineering, and wound healing systems. In drug delivery, surface chemistry and nanoscale architecture regulate drug-material interactions and release behaviour, enabling controlled and sustained therapeutic performance. In tissue engineering, fibrillar structure and mechanical integrity support scaffold functionality by facilitating cell attachment and biological integration. In wound healing, structural stability and surface responsiveness contribute to the maintenance of a conducive healing environment. These findings collectively indicate that nanocellulose performance is not an intrinsic property alone, but rather the outcome of controlled material design shaped by extraction-driven modifications.

The analysis further reveals that oil palm fibre-derived nanocellulose presents significant opportunities as a biomedical material platform. Its origin from a renewable biomass source supports resource efficiency and aligns with broader material sustainability considerations. In addition, its adaptable surface chemistry enables functional modification, allowing the material to be tailored for diverse biomedical applications. The inherent compatibility of nanocellulose with biological systems further reinforces its relevance for use in environments that require safe and responsive material behaviour. These characteristics position oil palm-derived nanocellulose as a versatile and promising candidate within the development of advanced biomaterials.

At the same time, the reviewed literature identifies several limitations that currently constrain its broader application. The absence of standardised extraction and processing protocols leads to variability in material properties, limiting reproducibility and comparability across studies. Research efforts also remain relatively fragmented, with many studies focusing on isolated application domains rather than adopting integrative approaches that connect material design with multifunctional performance. In addition, inconsistencies in evaluation methods hinder the establishment of unified benchmarks for biomedical effectiveness. These challenges indicate that further methodological refinement and cross-domain integration are necessary to strengthen the consistency and applicability of research outcomes.

Overall, the evidence confirms that oil palm fibre-derived nanocellulose holds strong potential as a functional and adaptable biomaterial for drug delivery, tissue engineering, and wound healing applications. Its development is supported by a combination of tunable material properties and the availability of a consistent biomass resource, reflecting a balanced and value-oriented approach to material innovation. Advancing this field will depend on the establishment of more standardised processing frameworks, integrative research strategies, and application-oriented evaluations that collectively enhance the reliability and translational relevance of nanocellulose-based biomedical systems.

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Conflicts of interest

The author declares there is no conflict of interest.

References

1. Poblócki K, Pawlak M, Drzeżdżon J, et al. Clean production of geopolymers as an opportunity for sustainable development of the construction industry. *Sci Total Environ.* 2024;928:172579.
2. Lubis N, Gea S, Tarigan J. Lignocellulosic analysis from oil palm empty fruit bunches and crystallinity index analysis of cellulose nanofibers isolated via high pressure steam explosion. *AIP Conf Proc.* 2023.
3. Zhang Y, Mingyue Sun, Penghao Sun, et al. Injectable nanocellulose-based poly(lipoic acid) hydrogels with tunable rheology, strong adhesion and multifunctional bioactivity. *Carbohydr Polym.* 2026;380:125084.
4. Madusari S, Bindar Y, Prakoso T, et al. Ultrasound-assisted dilute acid medium of oil palm residues toward morphological and thermal properties. *AIP Conf Proc.* 2024.
5. Singh TA, Sharma M, Sharma M, et al. Valorization of agro-industrial residues for production of commercial biorefinery products. *Fuel.* 2022;322:124284.
6. AL-Rajabi MM, Teow YH. Synthesis of thermoresponsive composite hydrogel from Pluronic F127 reinforced by oil palm empty fruit bunches-extracted cellulose for silver sulfadiazine drug delivery. *Sustain Chem Pharm.* 2023;31:100939.
7. Yusup EM, Mahzan SB. The physical characteristics of composite bone scaffold fabricated from OPEFB-CMC, chitosan and HA. *Int J Mech Eng Robot Res.* 2018;7(5):466–470.
8. Pauzi N, Segaran SC, Mohamad S, et al. Silver nitrate concentration on silver nanoparticles formation attached on cellulose nanocrystal matrix. *Mater Today Proc.* 2023.
9. Sikder MBH, Shah Samiur Rashid, Mohd Hasbi Ab Rahim, et al. Enzymatic cellulose nanocrystal production from pretreated palm oil empty fruit bunch fibers. *Mater Today Proc.* 2022:249–253.
10. Khalili H, Kumarage S, Mathew AP. In operando characterization of nanocellulose-based water treatment materials using atomic force microscopy and synchrotron scattering. *Accounts Mater Res.* 2025;6(12):1451–1461.
11. Azizan A, Intan Suhada Azmi, Rosmaria Abu Darim, et al. Lignocellulosic ionic liquid pretreated biomaterial/biomass. *Mater Today Proc.* 2020:1688–1692.
12. Azra NA, Atiqah A, Fadhlina H, et al. Oil-palm based nanocellulose reinforced thermoplastic polyurethane for plastic encapsulation of biomedical sensor devices: water absorption, thickness swelling and density properties. *Appl Sci Eng Prog.* 2023;16(1).
13. Yunus M, Fahma F, Abidin Z, et al. Cellulose-based surgical threads from oil palm empty fruit bunches in wound healing on male Wistar rats. *Indian Vet J.* 2019;96(6):21–23.
14. Mohamad S, Abdullah LC, Jamari SS, et al. Remediation of the oil palm frond juice base medium via efficient pretreatment and dilution factor strategy for bacterial cellulose production yield enhancement. *Int J Biol Macromol.* 2025;311:143744.
15. Saputra OA, Apriansyah F, Puspitasari MP, et al. Antioxidant activity and controlled-release feature of quercetin loaded amines-functionalized magnetically porous cellulose. *J Appl Polym Sci.* 2022;139(10):51744.
16. Sheng LD, Adnan SA, Osman AF, et al. Thermoplastic starch biocomposites with cellulose and bentonite fillers. *AIP Conf Proc.* 2021.
17. To SW, Al-Ashwal RHA, Ab Latif N, et al. Synthesis and characterisation of biodegradable carboxymethyl cellulose microcarriers from oil palm empty fruit bunch for therapeutic applications. *Cellulose.* 2025;32(1):483–503.
18. Hamid FA, Loh SK, Wahab NA, et al. Pulp and paper from wood and oil palm biomass: current development, issues, challenges and opportunities. *Ind Crops Prod.* 2024;222:119938.
19. Azzra NA, Atiqah A, Fadhlina H, et al. Effect of nanofibril cellulose empty fruit bunch-reinforced thermoplastic polyurethane nanocomposites on tensile and dynamic mechanical properties for flexible substrates. *Polym Compos.* 2024;45(16):14633–14643.
20. Yahya EB, Abdul Khalil HPS, Ahmad MI, et al. Cleaner approach of preparing antibacterial bioaerogel scaffolds using oil palm waste nanocellulose. *Ind Crops Prod.* 2023;191:115897.
21. Fong JJM, Ibrahim A, Abdulah MF, et al. Optimizing yield of microcrystalline cellulose from empty fruit bunch via hydrolysis using ionic liquid. *IOP Conf Ser Mater Sci Eng.* 2018;429(1):012060.
22. Kassem MA, Ghalwash MM, Abdou EM. Development of nanoemulsion gel drug delivery systems of cetirizine; factorial optimisation of composition, in vitro evaluation and clinical study. *J Microencapsul.* 2020;37(6):413–430.
23. Salleh MM, Yahya A, Ibrahim Z, et al. Sustainable biorefinery concept of oil palm and forest plants value chains for renewable source of chemicals, materials, and energy. In: *Handbook of Biorefinery Research and Technology: Production of Biofuels and Biochemicals.* 2024:519–546.
24. Suteris NN, Amina Yasin, Izan Izwan Misnon, et al. Curcumin loaded waste biomass resourced cellulosic nanofiber cloth as a potential scaffold for regenerative medicine: an in-vitro assessment. *Int J Biol Macromol.* 2022;198:147–156.
25. Wong LC, Jia Huey Poh, Wan Ting Tan, et al. Cellulose hydrogel development from unbleached oil palm biomass pulps for dermal drug delivery. *Int J Biol Macromol.* 2023;224:483–495.
26. Tristantini D, Yunan A. Advanced characterization of microbeads replacement from cellulose acetate based on empty fruit bunches and dried jackfruit leaves. *E3S Web Conf.* 2018;67:04045.
27. Binma-ae H, Prasertsan P, Choorit W. Preparation and characterization of biopolymers recovered from palm oil mill effluent and their complex hydrogels compared to commercial xylan. *Waste Biomass Valorization.* 2020;11(10):5109–5121.

28. Tuan Mohamood NFA-Z, Abdul Halim AH, Zainuddin N. Carboxymethyl cellulose hydrogel from biomass waste of oil palm empty fruit bunch using calcium chloride as crosslinking agent. *Polymers (Basel)*. 2021;13(23):4056.
29. Babu NSA, Alawi R, Muttlib NAA, et al. A comprehensive review on oil palm fibre implementations in medical sector. *J Food Process Preserv*. 2023;2023:1206963.
30. Ribeiro AC, do Nascimento G, Vegini AA, et al. Nanocellulose hydrogels from palm (*Archontophoenix cunninghamiana*) residual biomass. *Next Mater*. 2025;9:101333.
31. Palpperumal S, Subbiah Sankaralingam, Chellapandian Balachandran, et al. Antioxidant, anticancer, hepatoprotective and wound healing activity of fucopyranose (sulfated polysaccharides) from *Padina pavonica* (L.). *Indian J Microbiol*. 2024;64(4):1805–1825.
32. Al-Rajabi MM, Haan TY. Green synthesis of thermo-responsive hydrogel from oil palm empty fruit bunches cellulose for sustained drug delivery. *Polymers (Basel)*. 2021;13(13):2153.
33. Sharma S, Sathasivam T, Rawat P, et al. Lycopene-loaded nanostructured lipid carrier from carboxymethyl oil palm empty fruit bunch cellulose for topical administration. *Carbohydr Polym Technol Appl*. 2021;2:100049.
34. Susi S, Ainuri M, Wagiman W, et al. High-yield alpha-cellulose from oil palm empty fruit bunches by optimizing thermochemical delignification processes for use as microcrystalline cellulose. *Int J Biomater*. 2023;2023:9169431.
35. Asohan AW, Hashim R, Ishak KMK, et al. Preparation and characterisation of cellulose nanocrystal/alginate/polyethylene glycol diacrylate (CNC/Alg/PEGDA) hydrogel using double network crosslinking technique for bioprinting application. *Appl Sci*. 2022;12(2):771.
36. Rakhmatia YD, Hastuti N, Novianti VMP, et al. Assessment of TEMPO-oxidized cellulose nanofibril incorporation on PLGA membrane characteristics for biomedical applications. *Cellul Chem Technol*. 2025;59(7-8):825–839.
37. Mohan D, Teong ZK, Sajab MS, et al. Intact fibrillated 3D-printed cellulose microfibrils/CaCO₃ for controlled drug delivery. *Polymers (Basel)*. 2021;13(12):1912.
38. Dungani R, Singh B, Karliati T, et al. Synergistic morphological and mechanical properties of pressed oil palm trunk CNF/TiO₂ composite for green innovative antibacterial food packaging. *Results Eng*. 2025;26:104655.
39. Sazuan NSA, Zubairi SI, Mohd NH, et al. Synthesising injectable molecular self-curing polymer from monomer derived from lignocellulosic oil palm empty fruit bunch biomass: a review on treating osteoarthritis. *Arab J Chem*. 2023;16(2):104500.
40. Maghfirah A, Fahma F, Lisdayana N, et al. On the mechanical and thermal properties of poly(vinyl alcohol)-alginate composite yarn reinforced with nanocellulose from oil palm empty fruit bunches. *Indones J Chem*. 2022;22(1):114–125.
41. Supramaniam J, Darren Yi Sern Low, See Kiat Wong, et al. Facile synthesis and characterization of palm CNF-ZnO nanocomposites with antibacterial and reinforcing properties. *Int J Mol Sci*. 2021;22(11):5781.
42. Hajidariyot T, Nutchanon Nuntawad, Panadda Somsaen, et al. Cryo-induced cellulose-based nanogel from *Elaeis guineensis* for antibiotic delivery platform. *Int J Mol Sci*. 2023;24(2):1230.
43. Cazier EA, Pham T-N, Cossus L, et al. Exploring industrial lignocellulosic waste: sources, types, and potential as high-value molecules. *Waste Manag*. 2024;188:11–38.
44. Méndez-Durazno C, Ramírez V, Carrillo NMR, et al. Comprehensive characterization of Ecuadorian lignocellulosic biomass in terms of their candidacy for bioenergy purposes. *Clean Energy*. 2025;9(3):128–145.
45. Muna N, Fauzi AAN, Setyaningsih D, et al. Isolation of microfibrillated cellulose from oil palm empty fruit bunches (EFB) through peracetic acid delignification and enzyme hydrolysis. *IOP Conf Ser Earth Environ Sci*. 2019;309(1):012063.
46. Susi S, Ainuri M, Wagiman W, et al. Effect of delignification and bleaching stages on cellulose purity of oil palm empty fruit bunches. *IOP Conf Ser Earth Environ Sci*. 2022;1116(1):012018.
47. Masri S, Mohd N, Abu Kasim NH, et al. 3D-bioprinted oil-based hydrogels: a sustainable approach for bone and dental regeneration. *Int J Mol Sci*. 2025;26(8):3510.
48. Wan Jusoh WNL, Denesh Mohan, Mohd Shaiful Sajab, et al. Nanocellulose-based biomaterial ink hydrogel for uptake/release of bovine serum albumin. *Polymers (Basel)*. 2023;15(4):837.
49. Abdullah MA, Bahamid AAA, Alshajrawi OMS, et al. Integrated biomaterials engineering of oil palm fibres and microalgae for bioenergy, environmental remediation, and conversion into value-added products. *IOP Conf Ser Earth Environ Sci*. 2020;448(1):012091.
50. Mohamad Zulkifli NAS, Ng K, Ang BC, et al. Fabrication of water-stable soy protein isolate (SPI)/carboxymethyl cellulose (CMC) scaffold sourced from oil palm empty fruit bunch (OPEFB) for bone tissue engineering. *Ind Crops Prod*. 2025;224:120325.
51. Yusuf J, Sapuan SM, Rashid U, et al. Hybridization of biocomposites with oil palm cellulose nanofibrils/graphene nanoplatelets reinforcement in green epoxy: a study of physical, thermal, mechanical, and morphological properties. *Nanotechnol Rev*. 2025;14(1).
52. Perrin L, Gillet G, Gressin L, et al. Interest of Pickering emulsions for sustainable micro/nanocellulose in food and cosmetic applications. *Polymers (Basel)*. 2020;12(10):1–14.
53. Sailah I, Fahma F, Sihite REM. The effects of CaCl₂ and cellulose concentrations on the cellulose/PVA/alginate-based filaments production by wet spinning. *Trends Sci*. 2022;19(18).
54. Ajayi SM, Samuel O Olusanya, Kehinde O Sodeinde, et al. Hydrophobic modification of cellulose from oil palm empty fruit bunch: characterization and application in Pickering emulsions stabilization. *Carbohydr Polym Technol Appl*. 2023;5:100282.
55. Chew SC, How YH, Hasan ZABA, et al. Recovery of bioactive compounds from oil palm waste using green extraction techniques and its applications. *Int J Food Sci Technol*. 2024;59(11):8101–8113.
56. Ajayi SM, Samuel O Olusanya, Kehinde O Sodeinde, et al. Application of hydrophobically modified cellulose from oil palm frond in Pickering emulsions stabilization. *Carbohydr Polym Technol Appl*. 2022;4:100248.
57. Parid DM, Rahman NAA, Baharuddin AS, et al. Effects of carboxymethyl cellulose extracted from oil palm empty fruit bunch stalk fibres on the physical properties of low-fat ice cream. *Food Res*. 2021;5(S1):1–7.
58. Abu Hassan NA, Farah Fazlina, Leong Pui Teng, et al. Characterization of hemicellulose-carboxymethyl cellulose blend films: enhancement of the physicochemical, thermal, and mechanical properties. *J Appl Polym Sci*. 2024;141(19):e55361.
59. Rahmi ID, Hambali E, Fahma F, et al. Isolation of cellulose nanofibers (CNF) from oil palm empty fruit bunches (OPEFB) and its application as particle stabilizer Pickering emulsion. *AIP Conf Proc*. 2024:3058.
60. Sholahuddin S, Dian Yosi Arinawati, Chandra Kurnia Setiawan, et al. Characterization of cellulose nanofiber (CNF) from steam-exploded palm oil kernel fibers followed by supermasscolloider. *IOP Conf Ser Earth Environ Sci*. 2024;1417(1):012038.
61. Ardiansyah H, Kusumaningrum M, Bahlawan ZAS, et al. Green pretreatment techniques for enhanced delignification of lignocellulosic biomass: a case study of biomass waste in Indonesia. *IOP Conf Ser Earth Environ Sci*. 2024;1381(1):012034.

62. Al-Rajabi MM, Haan TY. Effect of sodium hydroxide/urea/deionised water solution ratio on the solubility of oil palm empty fruit bunches extracted biocellulose. *ASM Sci J*. 2021;16:1–6.
63. Olunusi SO, Ramli NH, Fatmawati A, et al. Revolutionizing tropical fruits preservation: emerging edible coating technologies. *Int J Biol Macromol*. 2024;264:130682.
64. Jenol MA, Norizan MN. Morphological and structural characteristics of nanocellulose isolated from oil palm empty fruit bunch. In: *Nanocellulose: Harnessing Sustainability from Biomass to Biocomposites*. 2026:83–92.
65. Kong YL, Leong MY, Harun MY, et al. Characterization of crosslinked nanocellulose from oil palm frond fibers for enhanced drug-loaded hydrogels in antibacterial application. *Mater Lett*. 2025;401:139209.
66. de Sá Barros S, Las-Casas B, Pereira B, et al. Development of sustainable cellulose-based materials from oil palm bunch fiber waste from the Amazon region. *Polym Int*. 2025;74(11):958–964.
67. Daneshfozoun S, Abdullah MA, Abdullah B. Preparation and characterization of magnetic biosorbent based on oil palm empty fruit bunch fibers, cellulose and *Ceiba pentandra* for heavy metal ions removal. *Ind Crops Prod*. 2017;105:93–103.
68. Pauzi N, Mohamad S, Ghazali S, et al. Evaluation of glucose reduction for silver nanoparticles synthesis with nanocrystalline cellulose matrix. *Bionanoscience*. 2023;13(4):1695–1702.
69. Arif ZU, Khalid MY, Sheikh MF, et al. Biopolymeric sustainable materials and their emerging applications. *J Environ Chem Eng*. 2022;10(4):108159.
70. Mohaiyiddin MS, Ong HL, Othman MBH, et al. Swelling behavior and chemical stability of chitosan/nanocellulose biocomposites. *Polym Compos*. 2018;39:E561–E572.
71. Lim HJ, Cheng WK, Tan KW, et al. Oil palm-based nanocellulose for a sustainable future: where are we now? *J Environ Chem Eng*. 2022;10(2):107271.
72. Yebin Lee, Hyunwoo Choi, Haoyu Zhang, et al. Sensitive, stretchable, and sustainable conductive cellulose nanocrystal composite for human motion detection. *ACS Sustain Chem Eng*. 2021;9(51):17351–17361.
73. Olusanya SO, Ajayi SM, Olumayede EG, et al. Multiple Pickering emulsions stabilized by hydrophobic-hydrophilic cellulose from oil palm empty fruit bunch: application in encapsulation of vitamin B9. *Polym Bull*. 2024;81(8):7013–7033.
74. Alves da Silva JB, Santana JS, Lucas AdeA, et al. PBAT/TPS-nanowhiskers blends preparation and application as food packaging. *J Appl Polym Sci*. 2019;136(26):47699.
75. Low LE, Tey BT, Ong BH, et al. Palm olein-in-water Pickering emulsion stabilized by Fe₃O₄-cellulose nanocrystal nanocomposites and their responses to pH. *Carbohydr Polym*. 2017;155:391–399.
76. Azizan A, Faisal MKM, Khalid MN, et al. Cellulose Segal crystallinity index accuracy level from smoothing models on X-ray diffraction spectrum data using oil palm biomaterial. *AIP Conf Proc*. 2025.
77. Manimaran M, Norizan MN, Kassim MHM, et al. Tunable structural, thermal and colloidal properties of anionic cellulose nanocrystals from oil palm biomass/metal oxide nanoparticles hybrid nanocomposites. *Int J Biol Macromol*. 2025;322:146530.
78. Cafiso D, Athanasia Amanda Septevani, Camilla Noè, et al. 3D printing of fully cellulose-based hydrogels by digital light processing. *Sustain Mater Technol*. 2022;32:e00444.
79. Tarigan AS, Wirjosentono B, Zuhra CF. Preparation of low crystallinity nanocellulose using acid hydrolysis. *AIP Conf Proc*. 2023.
80. Chang XX, Nabisab Mujawar Mubarak, Shaukat Ali Mazari, et al. A review on the properties and applications of chitosan, cellulose and deep eutectic solvent in green chemistry. *J Ind Eng Chem*. 2021;104:362–380.
81. Mahmood H, Moniruzzaman M, Iqbal T, et al. Comparative effect of ionic liquids pretreatment on thermogravimetric kinetics of crude oil palm biomass for possible sustainable exploitation. *J Mol Liq*. 2019;282:88–96.