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Review Article

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# From Oil Palm Residues to Advanced Biomedical Materials: A Review of Nanocellulose Scaffolds, Controlled Drug Delivery, Wound Dressings, and Antimicrobial Engineering

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## Abstract

Oil palm cultivation and processing generate abundant lignocellulosic residues that may be converted into functional nanocellulose for biomedical engineering. This qualitative literature review critically integrates peer-reviewed research published between 2020 and October 2026, connecting residue selection and cellulose isolation to material design, biological performance, translational readiness, and environmental implications. Particular attention is given to cellulose nanofibrils and cellulose nanocrystals directly obtained from oil palm empty fruit bunches, fronds, and trunks; evidence from other plant-derived nanocelluloses and microbially produced bacterial cellulose is interpreted separately. Four biomedical pathways are examined: tissue-engineering scaffolds, controlled drug delivery, wound management, and antimicrobial composites. Direct oil palm studies demonstrate feasible isolation and encouraging antibacterial scaffold and dressing performance, whereas many advanced drug-delivery and bioprinting functions remain supported predominantly by transferable, non-palm research. Material-specific risks include residual processing agents, endotoxins, particle persistence, sterilisation damage, variable feedstock quality, and incomplete clinical evidence. The review proposes a source-to-function-to-safety assessment framework and a staged research roadmap for clinically meaningful, traceable, and potentially lower-impact biomaterials. It concludes that promising laboratory functionality should be regarded as a foundation for controlled preclinical research rather than evidence of clinical efficacy.

**Keywords:** Oil palm residues, Nanocellulose, Cellulose nanofibrils, Cellulose nanocrystals, Biomedical scaffolds, Drug delivery, Wound dressings, Antimicrobial biomaterials, Biocompatibility, Circular bioeconomy

**JEL Classification:** I11, O13, O32, Q53, Q56.

## Introduction

### Background and Significance

Oil palm biomass is generally evaluated through agronomic productivity, food-system markets, bioenergy potential, and waste-management costs. A less developed perspective treats the fibrous residues of palm processing as a possible feedstock for high-purity functional biomaterials. Empty fruit bunches emerge during milling, while fronds and trunks arise during cultivation and replanting. Each represents a distinct physical and chemical substrate rather than a homogeneous stream of interchangeable waste. Recovery of cellulose from these sources may connect plantation-level resource efficiency with healthcare-oriented material innovation, but that connection requires evidence far more demanding than demonstrating nanoscale dimensions in a laboratory suspension [34,41,69]. Nanocellulose is an umbrella term for materials that differ in aspect ratio, crystallinity, surface chemistry, hydration behaviour, and manufacture. Cellulose nanofibrils, commonly abbreviated CNFs, form entangled high-aspect-ratio networks suitable for rheological control and mechanical reinforce-

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ment, cellulose nanocrystals, or CNCs, generally comprise shorter, relatively crystalline structures that can reinforce matrices and present chemically addressable surfaces. Bacterial nanocellulose, or BNC, is biosynthesised by microorganisms and is not physically extracted from palm fibre even when palm-derived sugars or frond juice supply its fermentation substrate. Keeping these categories, separate is fundamental to material attribution, comparability, and scientifically valid translation [40,53,58]. Biomedical materials must perform against the conditions of a specified therapeutic indication, which may involve wet tissues, physiological salts, living cells, inflammatory mediators, and repeated mechanical deformation. The relevant questions differ between a scaffold expected to support matrix deposition, a hydrogel expected to release a drug at a prescribed rate, and a dressing designed to manage exudate while limiting infection. A nanoparticle or polymer that is safe in one assay is not automatically safe in another anatomical site or route of exposure. Accordingly, a convincing case for palm-derived nanocellulose must bridge feedstock purity, functional architecture, appropriate biological endpoints, and intended-use-specific risk management [23,33,57].

### Research Problem, Urgency, and Contribution

Studies now demonstrate technically credible production of nanocellulose from oil palm empty fruit bunches, fronds, and trunks, including treatments based on acid hydrolysis, controlled oxidation, mechanical fibrillation, and deep eutectic solvents. Yet extraction feasibility often becomes conflated with biomedical readiness. A chemically characterised nanocrystal is not a validated carrier for parenteral delivery, an absorbent film is not necessarily an effective wound dressing, and a mechanically strong aerogel cannot be assumed to stimulate functional tissue regeneration. This review addresses the missing conceptual link between laboratory material properties and the application-specific standards of proof demanded by biomedical engineering [1,19,76]. There are reasons for cautious optimism. Palm-derived nanofibrils have been formulated into antibacterial aerogel scaffolds, and oil palm empty fruit bunch nanofibrils have been incorporated into curcumin-containing hydrogel dressings. A more recent experimental study explored nanocrystalline cellulose from oil palm waste within antioxidant-rich wound-dressing fibres. These studies are especially valuable because they test something beyond extraction yield: a plausible biomedical material configuration. Nevertheless, different formulations, organisms, assay durations, and outcome measures prevent a simple conclusion that any particular platform has demonstrated human therapeutic benefit [10,22,64]. The present review contributes a coherent interpretation rather than a numerical aggregation of outcomes. Its first contribution is an evidence-provenance classification that distinguishes direct palm-derived experimentation from cross-feedstock analogy and palm-fed microbial cellulose. Its second is a source-to-property-to-function mapping across four application families. Its third is an explicit analysis of trade-offs between green extraction, sterilizability, biosafety, mechanical function, and scalability. Its fourth is a translational roadmap that places cell-based data, animal models, manufacturing controls, and human evaluations in the correct sequence without implying that these gates have already been passed [5,33,40].

### Questions, Scope, and Organization

The review asks how oil palm residue characteristics shape the resulting nanocellulose, which processing and surface-engineering choices align with biomedical requirements, what direct evidence exists for scaffolds, drug delivery, wound dressings, and antimicrobial applications, how far findings from other feedstocks may be transferred, and which biological, regulatory, and environmental tests should be prioritized. Its objective is not to rank a universal best process but to explain the conditions under which an oil palm-derived material could become fit for a defined clinical purpose. Evidence published between 2020 and October 2026 is examined under a qualitative thematic literature-review design [30,47,66].

## Literature Review: Concepts and Theoretical Foundations

### Biomass Chemistry, Feedstock Heterogeneity, and Nanocellulose Families

Lignocellulosic residues contain cellulose associated with hemicellulose, lignin, extractives, ash, and process-dependent contaminants. Composition depends upon tissue anatomy, maturity, region, harvesting interval, moisture, and storage. Empty fruit bunches are readily concentrated at milling facilities but may contain entrained oil or inorganic material, fronds are geographically distributed and often wet, trunks contain spatially heterogeneous parenchyma and vascular bundles. Such heterogeneity affects the energy and chemical intensity of fibre opening and influences the residual chemistry of extracted nanocellulose. Therefore, medical development requires raw-material specifications and not merely a generic label of renewable fibre [34,41,69]. The distinction between CNFs and CNCs extends beyond terminology. Mechanical disintegration commonly preserves both crystalline and amorphous domains and generates flexible fibrillar networks with shear-thinning viscosity, while controlled acid hydrolysis preferentially removes less ordered regions to produce more crystalline particles. Surface charge, polydispersity, aggregation state, crystallite size, and water retention vary with extraction sequence. Biomedically relevant outcomes may include print fidelity, diffusional resistance, cell interaction, stress relaxation, and degradation persistence. A reporting scheme restricted to microscopy or FTIR peaks cannot establish functional equivalence between materials of different origins or processing histories [19,40,76]. Bacterial cellulose occupies an adjacent but separate technological pathway. It may produce a highly hydrated and relatively pure nanoscale network, and substantial research investigates its use in wound-care membranes and composite scaffolds. However, oil palm frond juice used as fermentation medium does not make the resulting cellulose a fibre-extracted CNF or CNC. Such studies remain highly relevant for circular utilisation and biomedical formulation, yet the taxonomy must be maintained in both discussion and comparative tables. Similarly, a successful composite based on coffee-derived nanocellulose is a

design analogy, not experimental confirmation for oil palm-derived material [45,53,58].

## Interface Engineering and Structure-Property-Function Relationships

Nanocellulose possesses abundant hydroxyl groups that permit hydrogen bonding, oxidation, esterification, grafting, and coordination with other materials. Surface modification may enhance aqueous stability, drug binding, cellular interaction, or incorporation within gelatin, alginate, chitosan, PVA, and other polymers. Yet the same modification can change charge density, water affinity, gelation kinetics, and toxicological behaviour. The relevant theoretical principle is that a biomedical function arises from interactions between architecture, surface chemistry, physiological conditions, and biological response, it cannot be inferred from cellulose identity alone [23,30,57]. Hydrogels exemplify this interdependence. More nanofibrils may improve mechanical integrity and shape retention, but dense fibrillar networks can reduce transport of oxygen or therapeutics and can impede cell infiltration. High swelling can support exudate uptake yet also weaken structural cohesion. Reactive crosslinking can provide durable or self-healing matrices, but remaining reagents and reaction by-products may require rigorous removal. The designer must optimise a multidimensional performance envelope rather than maximizing a single index such as tensile strength, crystallinity, or fluid absorption [2,44,57].

## Tissue Engineering and Regenerative Medicine

Tissue scaffolds operate as provisional microenvironments that may support cell attachment, migration, nutrient access, extracellular matrix deposition, and tissue-specific differentiation. For bone, construct stiffness, pore interconnectivity, mineral compatibility, and osteogenic signals matter, for cartilage, shape maintenance under compression and bioink extrusion behaviour may dominate, for skin, conformity, moisture balance, and infection control often become central. Nanocellulose can provide a fibrous matrix or reinforcing phase, but unmodified cellulose does not by itself reproduce every ligand and biochemical cue of natural extracellular matrix. Blending and biofunctionalisation are therefore common rather than optional additions in advanced scaffold design [12,25,29]. Contemporary research on cellulose nanofibril hydrogels also highlights a design tension between network strengthening and biological permissiveness. A hydrogel can exhibit excellent shape stability while still failing to sustain cell invasion, nutrient transport, or appropriate degradation behaviour. Recent materials reviews therefore support reporting printability, dynamic mechanics, sterility tolerance, and cell phenotype together, rather than relying on rheological performance alone [63]. A recent scoping review of cellulose nanocrystal-containing hydrogels likewise found that the biomedical evidence is concentrated in laboratory models and that translation towards clinical studies remains limited. Although its selection method differs from the present qualitative review, its findings provide a useful external check on the maturity of the broader technology. The priority for palm-derived candidates is therefore not only to reproduce favourable material properties but also to demonstrate how feedstock-specific composition and processing affect cellular performance under matched conditions [54]. The importance of composite design is illustrated by nanocellulose platforms containing hydroxyapatite, gelatin, chitosan, or bioactive agents. Studies on bone-oriented scaffolds have characterised cytocompatibility, mineral deposition, and cellular differentiation, while bioprinting studies emphasize shear-dependent rheology and construct fidelity. Such results identify useful hypotheses for palm CNFs and CNCs, although substituting the biomass source may alter suspension characteristics and impurities enough to invalidate straightforward extrapolation. The theoretical opportunity is genuine, but clinical readiness demands source-specific production and post-processing validation [35,37,46].

## Controlled Release, Wound Microenvironments, and Microbial Inhibition

A nanocellulose drug-delivery system may operate through sorption, molecular binding, encapsulation, diffusion-limited transport, matrix swelling, or a stimulus-responsive change in network structure. Release should be expressed as a profile under physiologically justified conditions rather than a single percentage at an arbitrary time. For proteins and growth factors, preservation of activity is as important as quantity released, for topical antimicrobials, local therapeutic exposure must be balanced against keratinocyte and fibroblast tolerance. Drug identity, dosage, target site, and device classification decisively influence the translational pathway [2,30,62]. Recent work extends this design logic toward molecularly informed carrier engineering. A 2026 review links nanofibril loading and release behaviour with experimental and computational analysis of drug-cellulose interactions, while experiments on carboxylated CNF aerogels show how pH-sensitive architecture can be investigated as a controllable design variable. Neither finding directly validates a palm-fibre-derived carrier, but both identify specific mechanisms and control experiments for subsequent palm-source comparisons [16,31]. Surface functionalisation can also be used to alter drug affinity without assuming that all additional retention is therapeutically beneficial. For example, mineral modification of bacterial nanocellulose dressings has been investigated as a route to prolong tetracycline retention and release, however, the evidence concerns the finished modified bacterial-cellulose system, not oil-palm-derived CNFs. A comparable palm-fibre experiment should distinguish drug binding, reversible release, residual drug activity and dose recovery after sterilisation, using otherwise identical controls [7]. Wound healing is a dynamic process involving inflammation, cell migration, angiogenesis, matrix deposition, and remodelling. A useful dressing maintains a favourable local environment and avoids excessive dehydration, maceration, trauma during removal, and uncontrolled release of antimicrobial constituents. Nanocellulose can contribute retention, capillarity, and mechanical support, while chitosan, curcumin, metal nanoparticles, polyphenols, or plant-derived oils may supply antimicrobial or antioxidant activity. Attribution is crucial: when an oil-palm-derived CNF hydrogel inhibits bacterial growth after curcumin addition, that result should not be described as proving intrinsic antibacterial action of cellulose [43,50,66].

### Biosafety, Translational Design, and Circular-Economy Logic

Biomedical acceptance depends upon material-specific safety rather than the broad reputation of a natural polymer. Potential hazards include residual alkali or acid, surface reagents, extractives, soluble degradation products, endotoxin contamination, particulate migration, inflammatory response, and changes caused by sterilisation. Even when a particular cell assay finds high viability, that result may not resolve haemocompatibility, genotoxicity, sensitization, systemic exposure, or long-term persistence. Exposure routes and contact durations must be matched to the eventual device or medicine [33,59,60]. The circular-bioeconomy justification is likewise conditional. Converting a residue into a high-value medical product may reduce disposal and substitute virgin raw materials, but chemical use, drying, purification, wastewater treatment, sterilisation, and quality assurance can dominate resource demand. Studies evaluating nanocellulose production pathways report considerable sensitivity to process selection and solvent recycling. Environmental superiority should therefore be demonstrated by life-cycle assessment with a transparent functional unit and a defensible benchmark, not asserted merely because the feedstock is agricultural waste [4,20,26].

## Method: Qualitative Literature Review

### Review Orientation and Interpretive Stance

This article uses a Qualitative Literature Review (QLR), not a systematic literature review or meta-analysis. Its purpose is conceptual integration of diverse experimental, review, environmental, and translational studies across materials science, pharmaceutics, tissue engineering, microbiology, and toxicology. The research questions require interpretation of mechanisms, comparability limits, and research gaps rather than pooled effect estimation. Consequently, the study does not claim exhaustive article capture, does not create PRISMA counts, and does not infer precision or statistical significance from a search process that was not designed for systematic synthesis [33,40,57].

### Literature Identification, Boundaries, and Appraisal

Relevant peer-reviewed literature dated January 2020 through October 2026 was identified through focused scholarly searches and citation chaining using concepts including oil palm empty fruit bunch, frond, trunk, CNF, CNC, bacterial cellulose, hydrogel, scaffold, drug release, wound dressing, antimicrobial, biocompatibility, and life-cycle assessment. Priority was assigned to identifiable journal articles with retrievable DOI or stable publication links and substantive methods or synthesis relevant to the review questions. Non-palm studies were retained where they clarified functional mechanisms, design standards, or known risks unavailable in direct palm-derived evidence. Research unrelated to cellulose, lacking a meaningful biomedical or manufacturing connection, or impossible to trace was not treated as substantive support [23,41,66]. Each article was interpreted through a source-and-function matrix: feedstock attribution, nanocellulose type, extraction and functionalisation, material configuration, biological model, principal outcome, safety information, and readiness for translation. The article's actual data-generating context was distinguished from authors' proposed applications. Stronger relevance was assigned to experimentally characterised materials with appropriate controls, justified endpoints, and reproducible processing conditions, mechanistic reviews supplied background rather than independent confirmation. This purposive, iterative reading supports transparent qualitative synthesis while acknowledging selection dependence and the absence of formal risk-of-bias scoring [22,44,64].

### Thematic Coding and Limitations

Analysis proceeded through repeated comparison of findings across six themes: feedstock and manufacturing, material architecture, tissue scaffolds, drug delivery, wound dressings and antibacterial composites, and safety, economics, and translation. Within each theme, claims were assigned to direct oil-palm fibre evidence, indirect plant-nanocellulose evidence, or bacterial-cellulose evidence. Conflicting or heterogeneous results were discussed through plausible methodological causes instead of averaged into a synthetic performance ranking. Interpretations were then mapped back to the review's research questions to develop a source-to-function-to-safety conceptual framework [40,48,53].

Table 1 formalises the evidence-provenance hierarchy used throughout the synthesis. It prevents studies employing palm-derived fermentation substrates or unrelated plant cellulose from being reported as direct fibre-extraction evidence. The distinctions are especially important when generalising biomedical effectiveness or claiming source-specific advantages (Table 1).

**Table 1:** Evidence-provenance classes and limits of inference for oil palm nanocellulose research.

| Evidence Class | Material Origin | Permissible Inference and Limitation |
|---|---|---|
| Direct palm-fibre CNF/CNC | CNF or CNC isolated from empty fruit bunches, fronds, or trunks. | Supports source-specific material and tested prototype claims. Does not establish clinical efficacy [22,64]. |
| Palm-fed bacterial cellulose | Bacterial cellulose biosynthesised on palm-derived juice or substrate. | Supports fermentation and composite findings. Must not be attributed to fibre-extracted CNF/CNC [58]. |
| Non-palm plant nanocellulose | Cellulose isolated from other biomass or commercial feedstocks. | Supports design mechanisms and hypotheses. Requires matched source-substitution experiments [40,63]. |

The categories in Table 1 define a constraint on the interpretation, not a hierarchy of intrinsic material quality. Non-palm and bacterial-cellulose work can be mechanistically valuable, but the central question of this review is what has actually been tested using oil palm fibres. Consequently, claims of safety and function must be returned to the source and formulation examined in each underlying experiment. The main methodological limitation is that a QLR cannot establish the completeness of a field or quantitative treatment effects. Numerous laboratory studies employ different cell lines, bacterial species, biomaterial dosages, humidity conditions, and wound models, so generalisability is limited. Publisher accessibility may also differ by subscription. The manuscript therefore uses cautious language—demonstrated, suggested, or hypothesized—according to the observed evidence tier and explicitly separates engineering opportunity from proven clinical effectiveness. These boundaries are particularly important when biomedical application claims are derived from non-palm feedstocks or from material characterisation alone [6,17,42].

## Results: Thematic Findings

### From Palm Fibre to Reproducible Cellulose Nanomaterials

Direct oil palm research confirms that CNFs and CNCs can be isolated from several residue streams. Hydrochloric-acid hydrolysis combined with sonication and hydrothermal processing has produced OPEFB-derived nanocrystals. Sequential oxidative extraction has yielded highly fibrillated cellulose from empty fruit bunches, while comparisons of frond pretreatments indicate that upstream processing changes the properties of CNCs used to reinforce hydrogel beads. These results collectively support feasibility and tunability, not a single universal quality profile. Feedstock-specific composition and process history should be disclosed alongside particle size, crystalline structure, and surface chemistry [1,19,76]. Oil palm trunk work provides an instructive example of a manufacturing trade-off. Partial delignification can reduce chemical use and preserve residual lignin, whereas more extensive purification may provide more uniform cellulose chemistry for sensitive biomedical use. Lignin-rich fibrils can be advantageous in industrial composites, but possible extractive-related irritation, sterilisation compatibility, and reproducibility remain unresolved when translated to living tissues. Hence an environmentally appealing reduction in bleaching cannot be equated with pharmaceutical-grade purity. A rational process pathway should distinguish industrial reinforcing cellulose from a higher-controlled medical-contact material [33,34,69]. Deep eutectic solvents and oxidative and mechanical combinations offer alternative pretreatments. Studies using DES with ultrasonication or high-pressure homogenization have optimised fibrillation outcomes and demonstrated that nanocellulose morphology can be tuned by solvent formulation and processing intensity. Pulsed-electric-field-assisted pretreatment has also been explored for CNC recovery from OPEFB. Their contribution is an expanded process design space, none obviates the need to quantify residual solvent, charge-modifying species, inorganic constituents, and batch-to-batch variations when the intended output will contact living tissue [21,47,56].

Figure 1 presents the feedstock-to-biomedical pathway. It deliberately distinguishes the generation of CNFs and CNCs from the subsequent functionalisation and validation of a specific device concept. The graphic should be read as a design logic rather than a claim that every depicted application has already been demonstrated experimentally using palm-derived cellulose (Figure 1) [40,41,64].

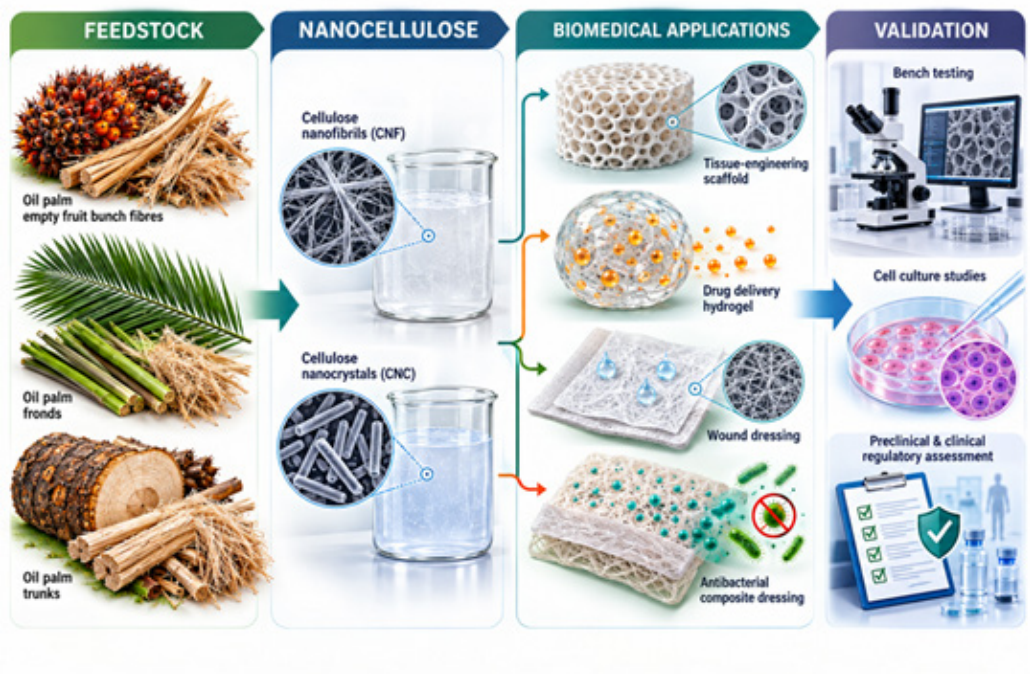



Figure 1: Oil palm residue conversion into nanocellulose and four biomedical design pathways (original conceptual illustration).

The essential implication of Figure 1 is that each transition introduces new evidence requirements. Extraction produces a material, blending creates a formulation, fabrication creates a prototype, biological tests assess context-specific response, and regulated manufacture requires reproducible specifications. Reversing this logic—beginning with broad therapeutic claims and seeking material properties afterward—risks conflating technical attractiveness with proven medical performance. Strong development programmes should assign acceptance criteria before choosing a particular solvent, crosslinker, drug, or antimicrobial additive [33,53,57].

## Scaffolds: Architectures for Skin, Bone, Cartilage, and Tissue Models

A particularly relevant direct palm study produced antibacterial bioaerogel scaffolds from oil palm empty fruit bunch CNFs using a modified supercritical carbon dioxide treatment, homogenization, and freeze-drying. The research incorporated chitosan to modify mechanical behaviour and cinnamon essential oil as an antibacterial agent. Reported material properties included very high porosity and promising responses in fibroblast-related testing. These findings support feasibility of a bioactive, porous palm-derived scaffold. However, a skin-regeneration hypothesis remains to be confirmed through standardised wound-healing models, safety studies, and comparisons with established dressings [43,64,66]. Nanocellulose's contribution to scaffold design may be structural rather than directly osteoinductive. Research from other feedstocks has generated composite structures with nanohydroxyapatite, gelatin, chitosan, or simvastatin and characterised cell proliferation, differentiation, and mineral formation. For bone tissue engineering, such composites use nanocellulose to support a hydrated architecture while other constituents provide mineral or biochemical cues. Palm-derived CNFs and CNCs might eventually substitute part of the reinforcing phase, but this must be experimentally verified with matched controls for purity, aspect ratio, and surface chemistry [35,37,46].

Three-dimensional bioprinting adds a further challenge because a bioink must flow through a nozzle without excessive shear injury, retain its printed shape, and remain accessible to nutrient exchange. The literature on nanocellulose-containing inks and cartilage-specific scaffolds indicates that fibril network rheology and cell-compatible crosslinking determine print quality. A method for fabricating self-standing nanocellulose scaffolds also emphasizes sequential printing, drying, and post-processing. For palm fibre applications, useful future studies would compare oil-palm CNFs against commercial benchmark CNFs under identical viscosity, cell viability, and mechanical recovery tests [25,29,38]. Other studies demonstrate that 3D printed polycaprolactone matrices reinforced by cellulose nanocrystals can be combined with metallic antimicrobial phases, and porous nanocellulose-derived networks may support tissue-related applications. Yet multifunctionality increases interpretation difficulty: a construct that inhibits bacteria because of released silver ions does not establish that the cellulosic reinforcement is antibacterial. Composite optimisation should measure ion release, local toxicity, strength retention, and cellular outcomes simultaneously rather than examining only an isolated microbial inhibition zone [3,12,39].

## Drug Delivery: Binding, Transport, and Release Precision

The transferability of nanocellulose-based drug delivery is conceptually strong because CNF and CNC surfaces can be integrated with alginate, PVA, chitosan, and other hydrogel matrices. Reviews describe particulate carriers, injectable gels, films, and stimuli-responsive formats engineered for prolonged or site-responsive release. However, the direct oil palm literature is much thinner than this general nanocellulose literature, a review should not label a delivery system palm-derived unless palm fibres were actually processed and incorporated. The correct claim is that validated carrier principles provide a plausible blueprint for subsequent palm-source material substitution [2,30,44]. A recent study on a pH-responsive carboxylated CNF composite aerogel reinforces the need to test release behaviour under more than one chemical environment. Such a comparison is informative only when the model drug's intrinsic solubility, matrix swelling, and release medium are documented alongside a mass-balance assessment. The published aerogel data offer a candidate testing protocol, not evidence that chemically different oil palm CNCs or CNFs will exhibit the same kinetics [16,31].

Mechanisms of drug release must be disentangled. An apparent sustained-release profile may arise from adsorption to charged cellulose surfaces, diffusional tortuosity through the hydrogel, swelling, erosion of a secondary polymer, or drug precipitation. Increasing CNF content can delay the apparent release of some model solutes but may also decrease total drug availability. Therefore, future studies should report loading efficiency, encapsulation efficiency, mass balance, release kinetics, medium composition, hydrodynamic conditions, drug stability, and dose recovered—not simply a favourable percentage-release curve. Source-specific nanocellulose comparisons require at least a commercial-cellulose control and a cellulose-free formulation [2,45,62]. For local wound delivery, drug selection should reflect the clinical indication. Curcumin, essential oils, and hydrogen-sulfide-releasing compounds have been examined in different composite platforms, while other studies explore nanoparticle-linked therapeutics. Their effects are not interchangeable: release rates, antioxidant activity, antibacterial response, irritation potential, and light sensitivity vary markedly across molecules. The dosage-form question also matters because a hydrogel that releases a soluble antimicrobial may operate under a different regulatory pathway from a structural dressing without a medicinal payload. Formulation development should consider these constraints at the design stage [11,22,75].

## Wound Dressings: Evidence Directly Relevant to Oil Palm Nanocellulose

A clear application-specific finding comes from a hydrogel constructed from PVA, PEG, OPEFB-derived CNFs, and curcumin. The study reported water retention, swelling, porosity, water-vapor

transport, and antibacterial behaviour, with stronger performance against a tested Gram-positive organism than against a tested Gram-negative organism. The result demonstrates an experimentally investigated palm-fibre composite with dressing-relevant attributes, not a clinically validated treatment. The limitation matters because assays against laboratory strains do not substitute for clinically realistic polymicrobial biofilms or patient-centered endpoints such as wound closure, pain, infection recurrence, or time to healing [22,42,66]. Recent advances also position nanocellulose wound dressings as engineered therapeutic and diagnostic interfaces. Controlled delivery of antimicrobial peptides from functionalised dressings illustrates how release testing can be linked to activity against wound pathogens, protease-sensing dressings illustrate a separate approach to monitoring infection-associated biomarkers. Both investigations used nanocellulose platforms that are not demonstrated as oil palm fibre-derived. Their immediate relevance is the definition of prospective experimental endpoints for palm CNFs, including peptide stability, release-dependent antimicrobial activity, sensor specificity, and performance in realistic wound fluid [15,71]. More advanced preclinical wound-dressing research illustrates both the opportunity and the evidence boundary. A 2026 bacterial-nanocellulose–hyaluronan construct was engineered for enzyme-responsive release of an antimicrobial peptide and evaluated in a contaminated porcine wound model, whereas an esculin-loaded bacterial nanocellulose study investigated inflammatory and tissue-remodelling responses in an animal model. These results supply more demanding benchmarks for mechanistic and preclinical evaluation, but neither is a clinical trial of oil-palm-fibre-derived nanocellulose. They strengthen the rationale for designing indication-specific test sequences rather than extrapolating directly from antibacterial or antioxidant assays [14,72,73].

The most useful performance comparison is multidimensional. Dressings must accommodate moisture and oxygen flux while retaining physical integrity when wet, excessively strong adhesion can cause tissue trauma at removal, and very high absorption can be inappropriate for a relatively dry wound. Nanocellulose's structural role can be advantageous because it permits manipulation of capillarity, strength, and flexibility. Nevertheless, successful dressing formulation requires appropriate assays for water-vapor transmission, simulated exudate, wet handling, microbial control, and cytocompatibility under clinically relevant conditions. A laboratory optimum expressed only by moisture retention is not necessarily a patient optimum [43,57,67]. Comparative work using bacterial cellulose and other plant-derived nanocellulose confirms that hydrogels can be engineered for self-healing, sustained release, antimicrobial and antioxidant response, and in some cases animal wound models. A bacterial nanocellulose hydrogel with bitter almond oil nanoemulsion and a cellulose-nanofibre-reinforced multifunctional composite are useful design examples. They are not direct evidence about palm fibre safety or performance, but they indicate meaningful endpoints for future studies of oil-palm-derived materials: epithelialization, granulation quality, collagen deposition, angiogenesis, irritation, and strength throughout dressing use [8,18,74]. A recent study involving nanocrystalline cellulose from oil palm waste in antioxidant-rich fibres extends the range of palm-related wound-dressing concepts beyond simple hydrogels. This points toward electrospun or fibrous layered constructions where structural cellulose, a carrier polymer, and a protective bioactive component are combined. The transferability of these findings depends on accurately documenting cellulose origin, component ratios, surface functionality, and the experimental distinction between antioxidant assays and biologically meaningful healing. Such studies reinforce the central theme: an agricultural residue can be upgraded into a promising platform, but mechanisms and efficacy must remain linked to tested formulations [10,11,64].

## Antimicrobial Composites and the Danger of Over-Attribution

Unmodified nanocellulose is principally a structural, hydrated, and surface-functional material rather than a universal antimicrobial drug. Antimicrobial behaviour can be imparted by chitosan derivatives, polyphenols, essential oils, silver or copper nanoparticles, and covalently attached functional groups. The result depends on bacterial species, microbial burden, agent concentration, contact time, and the matrix release profile. Consequently, comparing inhibition zones across studies without normalizing payload and assay conditions may be misleading. A defensible interpretation attributes observed activity to the tested composite and treats cellulose as one participating component until appropriate controls establish more specific causality [50,67,68].

Studies of bacterial-cellulose composites provide useful antimicrobial testing lessons without establishing direct palm-fibre equivalence. In one study, nanoparticle- and borax-containing bacterial cellulose was assessed using both biofilm biomass and metabolic-activity assays, a distinction that exposes limitations of a single inhibition-zone result. Separately, a collagen-nanocellulose-lignin hydrogel study explored multi-component antibacterial design, while a recent review examined bacterial nanocellulose as an antimicrobial carrier. These sources support broader and better-controlled experiments rather than stronger efficacy claims for untested palm-derived formulations [27,32,70]. Further composite studies emphasise why antimicrobial activity must be assessed together with material and host-response outcomes. Nanocellulose–chitosan hydrogel experiments connect composite structure to mechanical and antibacterial measurements, while an antimicrobial-peptide/silver-nanoparticle dressing design adds the challenge of quantifying activity attributable to each agent. Comparative evaluation of nanocellulose–silver composites in different forms also highlights the importance of toxicity testing alongside bacterial suppression. These studies provide methodological templates but do not establish the safety or efficacy of palm-fibre materials unless their fabrication and characterisation are repeated with those materials [13,28,51].

Direct palm-related antimicrobial evidence includes CNF-chitosan-cinnamon essential-oil aerogels and curcumin-containing OPEFB CNF hydrogels. Separately, bacterial cellulose produced using oil palm frond juice has been impregnated with silver nanopar-

ticles for dressing research. These are distinct material lineages. In the latter, the primary cellulose-forming organism and silver nanoparticle system determine essential aspects of material identity and effect, the palm substrate supports a circular fermentation route rather than providing physically isolated palm CNFs. Combining the three without provenance qualifiers would overstate what is known about fibre-derived materials [22,58,64]. An effective antimicrobial dressing should suppress problematic pathogens while protecting host cells and controlling unwanted systemic release. Functionalized bacterial cellulose composite studies show how crosslinking sequence can change water retention, drug release, and antibacterial response. Antimicrobial metal-containing scaffolds further demonstrate that enhancing microbial suppression can introduce ion-related exposure and biocompatibility challenges. The clinically relevant optimisation target is therefore therapeutic selectivity under a realistic exposure profile, not maximal microbial killing in a simplified broth or agar assay [18,39,68].

Figure 2 integrates these four application pathways and identifies the primary questions that must be answered before material performance is compared. It is a conceptual synthesis assembled for this review, not a statistical comparison of existing products or a product-readiness certification [2,40,57]. The distinctions shown also help readers separate preliminary prototype performance from the different safety and quality thresholds required for an eventual regulated product (Figure 2).

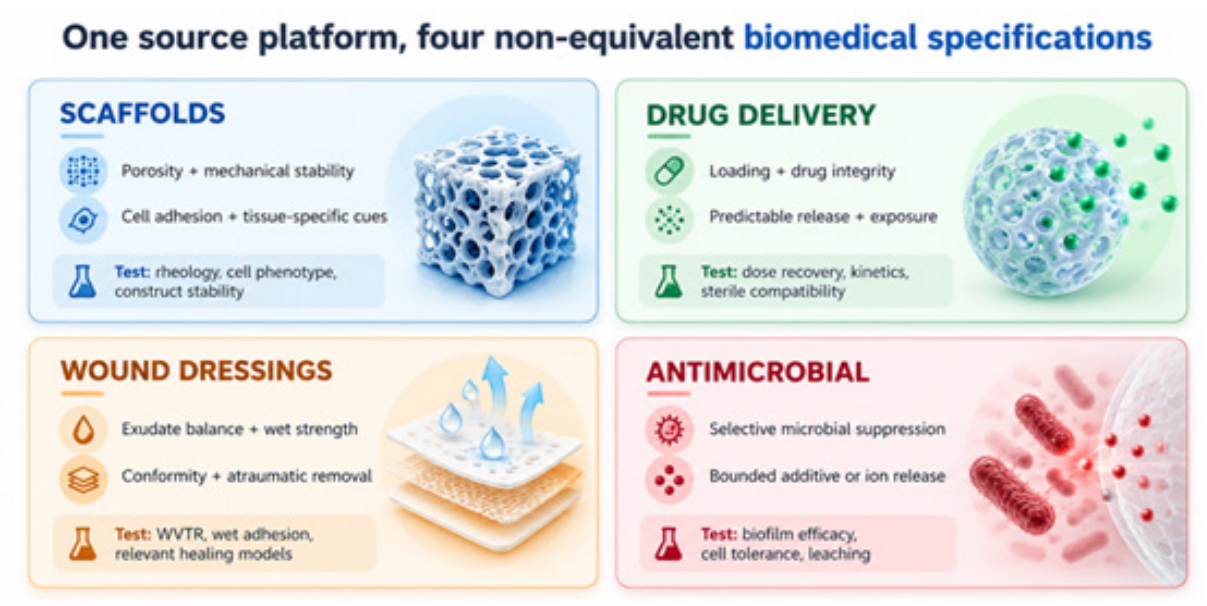



Figure 2: Different engineering acceptance criteria across four biomedical application families (authors' synthesis).

The application matrix in Figure 2 underscores that a single standardised nanocellulose grade will rarely optimise all four functions. Bioprinting demands predictable rheology and cell compatibility, whereas topical delivery emphasizes drug stability and reproducible release, dressings demand wet handling and exudate control, and antimicrobial composites demand selective activity without host toxicity. The optimal processing pathway should therefore be selected backwards from intended use and verified forwards through appropriate characterisation and biological testing [25,44,66].

## Safety Signals, Manufacturing Economics, and Evidence Gaps

The safety literature challenges the simplistic equation of bio-based origin with harmlessness. Research on inhalation exposure, pulmonary inflammation, and genotoxicity indicates that material size, length, surface functionalisation, dose, and route influence biological responses. Studies of some nanocellulose variants find limited effects under defined conditions, whereas other exposure scenarios demonstrate inflammatory changes or uncertain long-term outcomes. These observations do not prove that a hydrogel dressing will cause the same effects as an inhaled dry powder, rather, they show that route-specific risk characterisation is indispensable [17,24,52]. *In vitro* human-cell and animal research has examined DNA damage, cytotoxicity, immune endpoints, and oral or inhalation exposure. Such results often resist simple generalisation because the test materials differ in fibril dimensions, oxidation chemistry, dispersion, and purification. For medical applications, the appropriate question is whether a particular device material is acceptably safe under the projected tissue-contact category and exposure duration. At minimum, direct palm-derived formulations should undergo chemical-residue analysis, endotoxin testing, sensitization and irritation assessment, and application-matched cytotoxicity studies before claims of general biocompatibility [59,60,61]. Safety interpretation must also account for exposure pathways outside clinical use. Production workers may encounter aerosols during dry handling, consumers may encounter degradation particles, and disposal may introduce composite additives into

waste streams. Reviews of oral exposure and experiments using bacterial nanocellulose demonstrate the complexity of translating findings across material forms and physiological compartments. By design, a wound-dressing study neither establishes inhalation safety for manufacturing personnel nor predicts systemic disposition of an injectable carrier. A life-cycle safety strategy should connect production, product contact, and post-use management [6,55,65]. Economic and environmental results provide a counterweight to unconditional sustainability claims. OPEFB production analyses indicate that solvent recovery may substantially alter cost and greenhouse-gas outcomes, while comparative life-cycle work on nanocellulose more generally demonstrates large variation among treatments. The proper functional unit for a biomedical material may be a clinically equivalent dressing or an effective treatment episode, not merely a kilogram of dry nanocellulose. At present, sufficient clinical-performance and production data are rarely available for that stronger comparison. Thus, palm-residue-derived feedstock is an opportunity for sustainability, not a completed sustainability assessment [9,36,49].

## Discussion and Analysis

### Integrating Evidence to Answer the Research Questions

The answer to the first research question is that feedstock identity affects both processing and the eventual biomaterial. Empty fruit bunches, fronds, and trunks differ in tissue architecture and non-cellulosic components, they respond differently to delignification, hydrolysis, and fibrillation. The resulting differences in particle length, crystallinity, charge, rheology, and residue chemistry may influence every downstream application. The evidence supports multiple technically viable inputs but does not yet establish equivalence among them for medical use. Researchers should therefore specify source, sampling conditions, pretreatment, purification, and acceptance ranges rather than grouping all oil palm residues into one material class [19,41,69]. The second question concerns processing and surface engineering. The literature points to designable trade-offs rather than a winner among acid hydrolysis, oxidative processes, and eutectic-solvent approaches. A method favourable in yield may increase chemical cleanup, another may preserve residual lignin that assists reinforcement but complicates medical contact, a third may reduce solvent demand but increase energy for mechanical processing. The correct decision criterion is a multivariable specification that includes biochemical purity, dispersibility, wet performance, sterility compatibility, process efficiency, and reproducibility. A plausible development strategy would compare two or three extraction routes against the same application-specific functional targets [1,21,56].

The third question concerns the extent of direct biomedical evidence. The strongest visible oil palm fibre-derived work lies in porous antibacterial scaffold prototypes and composite wound dressings, with further relevant research on oil palm waste nanocellulose within antioxidant fibres. Most detailed experiments on injectables, sustained delivery carriers, bone scaffolds, advanced bioprinting, and cell-laden constructs derive from non-palm or bacterial sources. These other studies legitimately establish hypotheses, mechanism families, and analytical methods. They do not demonstrate interchangeability of feedstocks or clinical efficacy of palm-derived formulations. Accordingly, conclusions must follow the specific material and endpoint actually tested [10,22,64]. The fourth question concerns translation. A reasonable near-term focus is ex vivo and topical materials where prototype characterisation and local exposure can be evaluated in a staged manner. This is a prioritisation hypothesis, not a claim that topical devices face no regulation or that injectable biomaterials are inherently unsafe. Injectable drug carriers impose more elaborate control over particle behaviour, sterile processing, route-related toxicity, dosage, and pharmacokinetics. Bone and cartilage constructs may require long-duration integration and rigorous mechanical testing. The application should be chosen according to an explicit unmet need, access to appropriate models, and a realistic path to regulated evidence [2,29,33].

### The Source-to-Function-to-Safety Framework

The proposed framework contains six linked decision domains: (1) provenance and feedstock variability, (2) extraction and contaminant control, (3) material morphology and interface chemistry, (4) application-specific performance, (5) biological safety, and (6) scalable manufacturing and environmental assessment. It begins with the intended medical use and identifies measurable acceptance criteria at every upstream step. For example, a moist wound dressing may require limits for residual reagents, specified particle-size distributions, target water-vapor transmission, wet adhesion, antimicrobial selectivity, and post-sterilisation stability. A scaffold for bone repair would use a substantially different set of functional gates [23,33,57]. This approach avoids an influential conceptual error: treating resource recovery, biological performance, and sustainability as a linear chain of automatic benefits. A waste stream can have low acquisition cost and still generate an expensive biomedical product after washing, dialysis, drying, functionalisation, sterilisation, and quality control. Similarly, a composite with impressive *in vitro* antibacterial activity may have an unacceptable host-cell exposure profile. The design framework therefore requires explicit trade-off decisions and rejection thresholds rather than assuming that improvements in an isolated material variable represent progress toward patient benefit [26,49,50].

Figure 3 portrays these decision gates. The figure is intended to guide future comparative studies and the structure of application-specific research programmes, not to suggest a universal regulatory checklist. Regulatory classification must follow the device's actual intended purpose, constituent drugs or biologics, exposure route, jurisdiction, and claim language [4,33,53] (Figure 3).

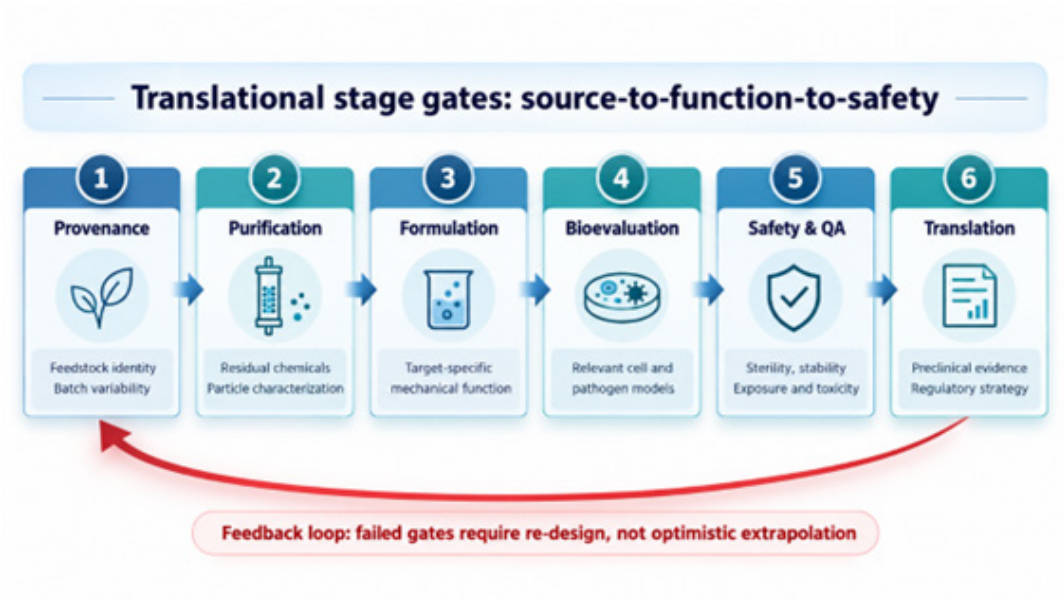



Figure 3: Iterative stage-gate model for oil palm nanocellulose translational research (authors' synthesis).

The most critical insight from Figure 3 is that the translational pathway contains feedback loops. Failure at the sterility or inflammatory-response gate may require redesigning purification and surface chemistry, not merely adding an extra test at the end. Likewise, an unfavorable life-cycle result may justify replacing a solvent or recovering process heat, provided that any production change triggers renewed material comparability testing. This iterative design is more realistic than a one-directional sequence from residue extraction to commercialization [20,36,48].

## Prioritization Across Four Biomedical Domains

Wound dressings currently provide the most direct palm-derived formulation evidence and an intuitive pathway for functional benchmarking. A priority programme could compare a palm-CNF base material with a commercial CNF control, formulate additive-free and additive-containing films, test reproducible wet handling and water balance, and then advance to relevant infection and healing models. An important objective would be determining whether the palm-derived fibrils meaningfully improve the composite after controlling for chitosan, curcumin, essential oils, and other active ingredients. Without this comparison, the specific contribution of upcycling palm fibres remains uncertain [22,42,64]. Such prioritisation should be interpreted in the light of the different levels of evidence available across source classes. Advanced bacterial-nanocellulose dressing studies can inform the choice of animal models, antimicrobial selectivity measures and clinically meaningful healing endpoints, but they cannot replace source-specific comparisons for oil-palm CNFs. Translational claims should clearly state whether a conclusion is based on materials characterisation, in vitro biological testing, an animal model or human evidence [54,72].

Table 2 translates the four application themes into practical prototype-evaluation priorities. Its metrics are indicative endpoints rather than universal pass-fail thresholds, because acceptable ranges depend on the tissue, intended exposure, payload, and local regulatory classification. Each experimental programme must specify its own comparator and pre-agreed acceptance criteria (Table 2).

Table 2: Application-specific experimental priorities for palm-derived nanocellulose prototypes.

| Application | Priority Measurements | Essential Comparator |
|---|---|---|
| Tissue scaffold | Wet mechanical stability, pore accessibility, cell identity, tissue-specific function. | Commercial CNF/CNC and an unreinforced scaffold. |
| Controlled delivery | Loading mass balance, drug integrity, release kinetics, relevant medium, leachables. | Free drug and cellulose-free vehicle. |
| Wound dressing | Moisture transfer, wet handling, adhesion, viable-cell response, healing-relevant endpoints. | Benchmark commercial dressing and additive-free composite. |
| Antimicrobial composite | Pathogen and biofilm response, active-agent release, host-cell selectivity, stability. | Active agent alone and matrix without active agent. |

The comparative strategy in Table 2 places functional attribution at the centre of future experimentation. Demonstrating favourable properties without a cellulose-free or active-agent-free control cannot separate the contribution of the palm-derived nanomaterial from its accompanying polymer or therapeutic ingredient. Standardised dose reporting and replicated production batches are therefore necessary for informative material comparisons. Tissue-engineering scaffolds are attractive but should initially target achievable functional demonstrations rather than broad claims of organ replacement. Researchers might select skin-equivalent culture substrates, acellular three-dimensional tissue models, or bone-related composite matrices and report standardised porosity, compressive behaviour, cell distribution, inflammatory response, and retention of structure. Follow-on experiments can compare nanocellulose fractions, polymer blends, and surface treatments. The most useful output of an early-stage study is a well-characterised structure-property-cell-response relationship that survives replication across production batches, rather than a single exceptional microscopy image [35,38,46]. Controlled delivery is scientifically promising because nanocellulose surfaces are chemically accessible, but the most defensible first claims concern formulation behaviour and local release, not systemic pharmacological equivalence. Proof-of-concept studies should specify a clinically relevant payload and incorporate controls for drug stability, total recovered mass, free drug, and cellulose-free vehicle. The mechanisms of binding and release should then be modeled against measured porosity and swelling rather than fitted to one convenient kinetic equation without physical justification. In vivo studies become meaningful only after sterile manufacturing and dose characterisation are reproducible [2,30,62]. Antimicrobial applications should prioritise selectivity and resistance-aware testing. A composite must be assessed against relevant Gram-positive and Gram-negative organisms and, where indicated, biofilm challenges, while parallel experiments measure host-cell viability and agent leaching. Metal-containing systems require particular attention to ion release, essential-oil systems require attention to concentration, volatility, stability, and possible irritation. Claims should identify whether microbial suppression is bacteriostatic, bactericidal, anti-adhesive, or simply associated with barrier function. The clinical goal is safe infection-risk reduction as part of wound management, not an isolated maximum inhibition zone [50,68,75].

## Biosafety, Sterilization, and Quality-by-Design Priorities

A practical medical-grade specification should include feedstock traceability, compositional limits, particle or fibril size distribution, charge or degree of oxidation, extractable and leachable substances, microbial bioburden, endotoxin load, and storage stability. The exact tests depend on use. Sterilization is not merely a final administrative step because irradiation, heat, ethylene oxide, or other methods can modify mechanical properties, hydrogel networks, loaded therapeutics, and extractable profiles. The actual chosen process must be validated on the final device formulation. No general conclusion of biological safety can substitute for these product-specific data [24,33,59]. An additional research priority is to differentiate release of therapeutic cargo from release of potentially harmful additives and particles. Antimicrobial peptide-loaded nanocellulose dressings and sensor-integrated formats show how added functions introduce multiple stability and performance attributes that require independent quality controls. For palm-derived prototypes, leachables, functional selectivity after sterilisation, and storage-time drift should be evaluated using the finished composite rather than inferred from isolated ingredient data [15,71]. In assessing antibacterial metal-containing composites, the same sample should be examined for antimicrobial performance, metal or particle release and biologically relevant toxicity after storage and sterilisation. Testing only a free antimicrobial agent or an untreated polymer matrix would be insufficient to resolve the effects of the integrated composite. The 2026 nanocellulose–silver study offers a pertinent example of examining both bacterial inhibition and potential adverse responses, although application-specific palm-derived testing remains necessary [28,51]. Animal and human findings must be interpreted according to dose and route. Pulmonary studies are important for occupational and respiratory-risk questions, oral toxicology can illuminate an ingestion pathway, yet neither directly determines skin-contact acceptability. Conversely, fibroblast survival following short exposure does not rule out chronic irritation or sensitization. Translational planning should identify realistic exposure scenarios and construct a battery of orthogonal assays, including appropriate negative and positive controls, before moving toward animal models. For systems designed to deliver drugs, pharmacokinetics, biodistribution, and clearance may become central [6,17].

## Environmental Performance and Industrial Implementation

Environmental claims should distinguish agricultural residue collection from downstream production burdens. Pre-treatment chemicals, mechanical energy, clean water, product purification, drying, sterile manufacture, and waste processing all contribute impacts. LCA studies of diverse nanocellulose routes find that the favored technology changes with system boundaries, solvent recovery, process energy, and feedstock assumptions. A cradle-to-gate analysis is a useful beginning but cannot establish environmental superiority of a medical product unless performance and end-of-life are considered. Moreover, allocation among palm-processing coproducts should be explicit to avoid attributing arbitrary burdens or credits to empty fruit bunches [4,9,26]. An oil palm-oriented assessment recently examined how deep eutectic solvent recovery changes CNC production cost and emissions. This offers a concrete example of why process design matters, but published scenarios should not be transferred uncritically to different geographic energy grids or medical-grade purity requirements. A sterile composite dressing may need different utilities and quality infrastructure than commodity CNC. Future scale-up studies should therefore report site-specific mass and energy balances, solvent make-up and losses, purification yield, rejection rates, and quality-control expenditures along with an appropriate comparator material [20,47,49]. There is also a governance dimension. Procurement specifications should distinguish residue classes, plantation sourcing and traceability, solvent and additive choices, consistency of supply, and medi-

cal-quality processing responsibilities. Collaboration between palm mills, polymer scientists, pharmacologists, clinicians, toxicologists, and manufacturing engineers is necessary because no single laboratory can validate all stages of the chain. Such partnerships should prioritise reproducibility and patient outcomes above rapid publication of new formulations. Scientific transparency is enhanced when the source identity and comparator design are documented well enough for independent replication [34,36,48].

### Research Agenda and Implications

A coherent near-term agenda involves three stages. First, establish comparative libraries of oil palm CNFs and CNCs with independently measured composition, morphology, charge, chemical residues, and batch variation. Second, select one target application and benchmark against commercial cellulose and a non-cellulosic control with appropriate biological endpoints. Third, validate the promising formulation under sterilisation, aging, toxicology, and application-relevant preclinical conditions while concurrently undertaking transparent manufacturing and environmental assessments. This sequence would produce stronger evidence than many disconnected demonstrations of extraction yield or general antimicrobial behaviour [21,38,69]. The conceptual novelty of this review lies in its insistence that evidence provenance is part of biomedical material quality. A direct palm fibre experiment establishes a different claim than a bacterial-cellulose film fermented on palm juice or a bone scaffold built from generic commercial nanocellulose. All can inform innovation, but only the former directly tests the targeted material lineage. When the literature is read through this classification, oil palm-derived nanocellulose appears as an emerging translational candidate with substantive proof of manufacturing feasibility and promising local-material prototypes, rather than an already established clinical technology across all four application areas [53,58,64].

## Conclusion

Oil palm fibre-derived nanocellulose offers a credible route for converting agricultural residues into functional platforms for biomedical engineering. The strongest current case is based on feasible extraction from empty fruit bunches, fronds, and trunks, and on early composite prototypes for wound care and porous antibacterial scaffolds. Its potential roles in drug delivery and advanced regenerative scaffolds are scientifically plausible, but much of the relevant design evidence currently comes from other plant biomass or from bacterial nanocellulose. This distinction must remain visible in any substantive claims about performance and readiness. Across all four applications, the decisive question is not whether nanocellulose can be produced from palm residues, but whether a specified, reproducible material improves a clinically meaningful function without introducing unacceptable risks. Answering that question requires attention to source provenance, impurity control, network architecture, controlled release, microbial selectivity, living-cell compatibility, long-term exposure, and sterilisation. A biomaterial should be evaluated as its finished formulation rather than as an isolated cellulose fraction or an appealing microscopy image. The practical recommendation is to prioritise indication-led development, particularly rigorously benchmarked local wound-care formulations and carefully defined scaffold prototypes. Each programme should use commercial and additive-free controls, measure relevant biological endpoints, disclose manufacturing and purification details, and advance only through appropriate preclinical and regulatory gates. Claims of antimicrobial efficacy must identify the active composite constituents, and environmental advantages should be tested with transparent life-cycle and economic boundaries rather than assumed from waste-derived feedstock identity. Ultimately, oil palm-derived CNFs and CNCs merit sustained research at the intersection of circular resource use and advanced healthcare materials. Their most promising future depends on discipline in experimental attribution and thoughtful collaboration between plant-biomass processing, biomaterials engineering, and clinical research. The transition from attractive laboratory concept to useful healthcare technology will be achieved through rigorous comparative evidence, reproducible manufacture, and demonstration of safety and benefit under the conditions in which the material is actually intended to operate.

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None.

## Conflict of Interest

None.

## References

1. Abd Manaf, Shuhaida Harun, Jamaliah Md Jahim, Mohd Shaiful Sajab, Zulkifli Ibrahim, et al. (2024) Synergistic sequential oxidative extraction for nanofibrillated cellulose isolated from oil palm empty fruit bunch, PLOS ONE 19(6): e0299312.
2. Ai Y, Zhongxin Lin, Wenqi Zhao, Mei Cui, Wei Qi, Renliang Huang, et al. (2023) Nanocellulose-based hydrogels for drug delivery, Journal of Materials Chemistry B 11(30): 7004-7023.
3. Anitasari S, Hendrik Setia Budi, Yung Kang Shen, Yuliana Mahdiyah Daat Arina (2024) New Insight of Scaffold Based on Hydroxyapatite (HAp)/ Bacterias Nanocellulose (BN) for Dental Tissue Engineering, European Journal of Dentistry 18(3): 891-897.
4. Arfelis S, Roberto J Aguado, Didem Civancik, Pere Fullana I Palmer, M Àngels Pèlach, et al. (2023) Sustainability of cellulose micro-/nanofibers: A comparative life cycle assessment of pathway technologies, Science of the Total Environment 874: 162482.
5. Babu A (2023) A Comprehensive Review on Oil Palm Fibre Implementations in Medical Sector, Journal of Food Processing and Preservation 1206963.
6. Brand W, Petra C E van Kesteren, Elmer Swart, Agnes G Oomen (2022) Overview of potential adverse health effects of oral exposure to nanocellulose, Nanotoxicology 16(2): 217-246.
7. Breijaert TC (2025) Functionalization of bacterial nanocellulose-based wound dressing for increased drug retention, Carbohydrate Polymer Technologies and Applications 10: 100756.
8. Chamchangi MA, Sajad Abdollahi, Zeinab Raoufi, Ahmad Ali Badr (2024) Nano hydrogel with bacterial nanocellulose and bitter almond oil nanoemulsions for enhanced wound healing: In-vivo and in-vitro characterization, International Journal of Biological Macromolecules 277(1): 134134.
9. Da Cruz TT (2024) Nanocelluloses as sustainable emerging technologies: State of the art and future challenges based on life cycle assessment,

Sustainable Materials and Technologies 42: e01010.

10. Dahlan NA (2026) Antioxidant-rich nanofibrous scaffolds from renewable lignin and nanocellulose for next generation wound dressings, Industrial Crops and Products 240: 122602.

11. Datta D, Sony Priyanka Bandi, Viola Colaco, Namdev Dhas, Suprio Shantanu Saha, Syed Zubair Hussain, et al. (2025) Cellulose-Based Nanofibers Infused with Biotherapeutics for Enhanced Wound-Healing Applications, ACS Polymers Au 5(2): 80-104.

12. De Lima TAM, Gabriel Goetten de Lima, Nimra Munir, Joana Raquel Teixeira Coutinho, Geoffrey Robert Mitchell, et al. (2023) Nanofibrillated cellulose originated from Rhododendron ponticum to produce scaffolds using 3D printing for biomedical applications, International Journal of Biological Macromolecules 253(1): 126556.

13. Deng N, Li Q, Wang W (2025) Design and Fabrication of Nanocellulose-Chitosan Composite Hydrogels with Enhanced Mechanical and Antibacterial Properties, Langmuir 41(21): 13604-13610.

14. Emaminia A, Mohammad Hashemnia, Hadi Cheraghi, Farid Rezaei (2025) A novel esculin-loaded bacterial nanocellulose wound dressing enhances cutaneous wound healing via modulation of inflammation, oxidative stress, and growth factor expression, International Journal of Biological Macromolecules 333(1): 148810.

15. Eskilson O, Emanuel Wiman, Nina Reustle, Jakob Langwagen, Zeljana Sotra, et al. (2025) Nanocellulose Wound Dressings with Integrated Protease Sensors for Detection of Wound Pathogens, ACS Sensors 10(6): 3953-3963.

16. Esmaeilzadeh A, Azimzadeh Irani M (2026) Nanocellulose-based drug delivery systems: experimental findings and computational insights with emphasis on cellulose nanofibers, Journal of Biomaterials Science Polymer Edition 1-33.

17. Fujita K, Sawae Obara, Junko Maru, Yuka Kawai, Shigehisa Endoh, et al. (2025) Pulmonary inflammation and immune responses induced by nanocellulose: Insights from in vivo and in vitro models, Current Research in Toxicology 9: 100259.

18. Gao Z, Yulun Li, Xingwei Li, Hongao Chen, Chengbo Li, et al. (2025) Bifunctional modified bacterial cellulose-based hydrogel through sequence-dependent crosslinking towards enhanced antibacterial and cutaneous wound healing, International Journal of Biological Macromolecules 296: 139737.

19. Hamidon TS, Nor Najhan Idris, Rohana Adnan, M K Mohamad Haafiz, Azeana Zahari, et al. (2024) Oil palm frond-derived cellulose nanocrystals: Effect of pretreatment and elucidating its reinforcing potential in hydrogel beads, International Journal of Biological Macromolecules 262(Pt 2): 130239.

20. Hoo DY (2024) Prospective life cycle assessment: Identifying the most promising methods for sustainable cellulose nanocrystal production, Chemical Engineering Journal 498: 154964.

21. Jafri NHS (2024a) Optimum Yield of Empty Fruit Bunches Cellulose Nanofibers by Deep Eutectic Solvent and Ultrasonication, Chemical Engineering & Technology 47: 56-67.

22. Jafri NHS (2024b) PVA-PEG Hydrogel Incorporated with Cellulose Nanofibril of Oil Palm Empty Fruit Bunches and Antibacterial Agent Curcumin, Journal of Pharmacy 4: 116-128.

23. Jiao H (2023) Recent advances in strategies of nanocellulose surface and/or interface engineering for potential biomedical applications as well as its ongoing challenges: a review. Cellulose 30: 6741-6771.

24. Joseph P, Christina M Umbright, Jenny R Roberts, Jared L Cumpston, Marlene S Orandle, et al. (2021) Lung toxicity and gene expression changes in response to whole-body inhalation exposure to cellulose nanocrystal in rats, Inhalation Toxicology 33(2): 66-80.

25. Jovic TH, Tamsin Nicholson, Hari Arora, Kim Nelson, Shareen H Doak, et al. (2023) A comparative analysis of pulp-derived nanocelluloses for 3D bioprinting facial cartilages. Carbohydrate Polymers 321: 121261.

26. Kane S, Sabbie A Miller, Kimberly E Kurtis, Jeffrey P Youngblood, Eric N Landis, et al. (2023) Harmonized Life-Cycle Inventories of Nanocellulose and Its Application in Composites, Environmental Science & Technology 57: 19137-19147.

27. Kart NB (2024) Evaluation of Anti-Biofilm and in Vitro Wound Healing Activity of Bacterial Cellulose Loaded with Nanoparticles and Borax, Journal of Polymers and the Environment 32: 5654-5665.

28. Kebede WB (2026) Antimicrobial Peptide-Modified Nanocellulose-Silver Nanoparticle Composite Wound Dressings, ACS Applied Nano Materials 9(3): 1571-1583.

29. Lin L (2023) Application of 3D-bioprinted nanocellulose and cellulose derivative-based bio-inks in bone and cartilage tissue engineering, International Journal of Bioprinting 9: 637.

30. Liu A, Hailian Wu, Abid Naeem, Qing Du, Bin Ni, et al. (2023) Cellulose nanocrystalline from biomass wastes: An overview of extraction, functionalization and applications in drug delivery, International Journal of Biological Macromolecules 241: 124557.

31. Liu X, Yang Li, Changjing Qiu, Zhongming Liu, Shoujuan Wang, et al. (2026) Design and characterization of a pH-responsive carboxylated cellulose nanofibril composite aerogel for enhanced drug delivery, International Journal of Biological Macromolecules 346: 150677.

32. Li X (2025) A collagen/nanocellulose/lignin hydrogel dressing mimicking to the plant cell wall for enhanced wound healing and bacterial inhibition, Industrial Crops and Products 228: 120872.

33. Li Y (2024) Biosafety consideration of nanocellulose in biomedical applications: A review, International Journal of Biological Macromolecules 265: 130900.

34. Mahardika M (2024) Recent Developments in Oil Palm Empty Fruit Bunch (OPEFB) Fiber Composite, Journal of Natural Fibers 21.

35. Mahmoudi M (2025) Structure-property-function relationships in 3D-printed gelatin/cellulose nanocrystals/n-HAP scaffolds for bone tissue repair, International Journal of Biological Macromolecules 328: 147790.

36. Mariño MA (2024) Recycled ionic liquid vs. deep eutectic solvent in cellulose nanocrystals production: Characterization, techno-economic analysis, and life cycle assessment, Journal of Cleaner Production 472: 143461.

37. Mohammadi S, Fahimeh Ghasemi, Seyyedeh Ameneh Alavi G, Esmat Alemzadeh (2024) Investigate the in vitro biocompatibility, biodegradation, cytotoxicity, and differentiation potential of 3-D gelatin-nanocellulose composite scaffolds loaded with nanohydroxyapatite and simvastatin, Tissue and Cell 91: 102536.

38. Mohan T, Matej Bračič, Doris Bračič, Florian Lackner, Chandran Nagaraj, et al. (2025) Protocol for the fabrication of self-standing (nano)cellulose-based 3D scaffolds for tissue engineering, STAR Protocols 6(1): 103583.

39. Ngatta KM, Edja Florentin Assanvo, Joelle El Hayek, Nathalie Masquelez, Pelagie Kamgang Syapnjeu, et al. (2025) 3D-Printed Polycaprolactone Scaffolds Reinforced with Cellulose Nanocrystals and Silver Nanoparticles for Bone Tissue Engineering, ACS Applied Materials & Interfaces 17(28): 41028-41043.

40. Ong XR, Adrielle Xianwen Chen, Ning Li, Yi Yan Yang, He Kuan Luo, et al. (2023) Nanocellulose: Recent Advances Toward Biomedical Applications, Small Science 3(22): 2200076.

41. Padzil FNM (2020) Potential of Oil Palm Empty Fruit Bunch Resources in Nanocellulose Hydrogel Production for Versatile Applications: A Review. Materials 13: 1245.

42. Pasaribu KM, Putu Mahendra, Myrtha Karina, Nanang Masruchin, Novia Amalia Sholeha, et al. (2024) A review: Current trends and future perspectives of bacterial nanocellulose-based wound dressings, International Journal of Biological Macromolecules 279(Pt4): 135602.

43. Patel DK (2022) Functionalized chitosan/spherical nanocellulose-based hydrogel with superior antibacterial efficiency for wound healing, Carbohydrate Polymers 284: 119202.

44. Patel DK, Keya Ganguly, Jin Hexiu, Sayan Deb Dutta, Tejal V Patil, et al. (2024) Nanocellulose-assisted mechanically tough hydrogel platforms for sustained drug delivery, International Journal of Biological Macromolecules 271: 132374.

45. Patel DK, Junmin Cha, So Yeon Won, Sung Soo Han (2025) Upcycled coffee waste into nanocellulose-reinforced alginate-carboxymethyl cellulose hydrogels for tunable drug delivery. International Journal of Biological Macromolecules 333(Pt 2): 148942.

46. Phatchayawat PP, Supansa Yodmuang, Muenduen Phisalaphong (2025) Bacterial Nanocellulose-Chitosan-Gelatin-Hydroxyapatite Scaffolds for Bone Tissue Engineering, Macromolecular Bioscience 25(11): e00299.

47. Putranto AW (2025a) Enhancement of cellulose nanocrystal yield from oil palm empty fruit bunches: A comparative study of binary and ternary deep eutectic solvents with pulsed electric field pretreatment, Biomass and Bioenergy 196: 107672.

48. Putranto AW (2025b) Life cycle assessment of deep eutectic solvent employment for sustainable nanocellulose production from biomass: a systematic review, Green Chemistry Letters and Reviews 18: 2507283.

49. Putranto AW (2025c) The role of deep eutectic solvent recycling on crystalline nanocellulose production from oil palm empty fruit bunch: A techno-economic viability and life cycle assessment study, Biomass and Bioenergy 203: 108306.

50. Ren L, Guoyi He, Yaxin Zhou, Jie Dai, Wenjun Miao, et al. (2022) A hydrogel based on nanocellulose/polydopamine/gelatin used for the treatment of MRSA infected wounds with broad-spectrum antibacterial and antioxidant properties and tissue suitability, Biomaterials Science 10(12): 3174-3187.

51. Ribeiro LG, Yelin Ko, Juan P Hinestroza, Edison Barbieri, Ana Olivia de Souza, et al. (2026) Nanocellulose-Silver Nanoparticle Nanocomposites for Hydrogel, Aerogel, and Film Development: Antibacterial Properties and Toxicity Evaluation, ACS Omega 11(25): 37780-37789.

52. Sai T, Fujita K (2020) A review of pulmonary toxicity studies of nanocellulose, Inhalation Toxicology 32(6): 231-239.

53. Samyn P, Amin Meftahi, Sahar Abbasi Geravand, Mohammad Ehsan Momeni Heravi, Hamideh Najarzadeh, et al. (2023) Opportunities for bacterial nanocellulose in biomedical applications: Review on biosynthesis, modification and challenges. International Journal of Biological Macromolecules 231: 123316.

54. Seneviratne DM, Eliza J Whiteside, Louisa C E Windus, Paulomi Polly Burey, Raelene Ward, Pratheep K Annamalai, et al. (2025) Emerging Biomedical Applications of Sustainable Cellulose Nanocrystal-Incorporated Hydrogels: A Scoping Review, Gels 11(9): 740.

55. Shipelin VA (2024) Toxicological Characteristics of Bacterial Nanocellulose in an In Vivo Experiment-Part 2: Immunological Endpoints, Influence on the Intestinal Barrier and Microbiome, Nanomaterials 14: 1678.

56. Sonyeam J, Ratanaporn Chaipanya, Sudarat Suksomboon, Mohd Jahir Khan, Krongkarn Amatariyakul, et al. (2024) Process design for acidic and alcohol based deep eutectic solvent pretreatment and highpressure homogenization of palm bunches for nanocellulose production, Scientific Reports 14(1): 7550.

57. Tamo AK (2024) Nanocellulose-based hydrogels as versatile materials with interesting functional properties for tissue engineering applications, Journal of Materials Chemistry B 12(32): 7692-7759.

58. Tan SM (2024) Bacterial cellulose production from oil palm frond juice and its impregnation with silver nanoparticles for antibacterial wound dressing, Journal of Oil Palm Research 36: 664-673.

59. Ventura C, Fátima Pinto, Ana Filipa Lourenço, Jorge F S Pedrosa, Susete N Fernandes, et al. (2023) Assessing the Genotoxicity of Cellulose Nanomaterials in a Co-Culture of Human Lung Epithelial Cells and Monocyte-Derived Macrophages, Bioengineering 10(8): 986.

60. Vital N, Célia Ventura, Michel Kranendonk, Maria João Silva, Henriqueta Louro, et al. (2022) Toxicological Assessment of Cellulose Nanomaterials: Oral Exposure, Nanomaterials 12(19): 3375.

61. Vital N, Maria Cardoso, Michel Kranendonk, Maria João Silva, Henriqueta Louro, et al. (2025) Evaluation of the cyto- and genotoxicity of two types of cellulose nanomaterials using human intestinal cells and in vitro digestion simulation, Archives of Toxicology 99(2): 575-596.

62. Wang Y, Ying Zhang, Hao Zhong, Minghui Guo, Xueqi Chen, et al. (2025) Construction of a non-toxic interpenetrating network hydrogel drug carrier supported by carbon microspheres and nanocellulose, Carbohydrate Polymers 350: 123035.

63. Won T, MeeiChyn Goh, Chaewon Lim, Jieun Moon, Kyueui Lee, et al. (2025) Recent Progress in Cellulose Nanofibril Hydrogels for Biomedical Applications, Polymers 17(17): 2272.

64. Yahya EB (2023) Cleaner approach of preparing antibacterial bioaerogel scaffolds using oil palm waste nanocellulose, Industrial Crops and Products 191: 115897.

65. Yamashita Y, Akinori Tokunaga, Koji Aoki, Tamotsu Ishizuka, Hideyuki Uematsu, et al. (2024) Assessing the Safety of Mechanically Fibrillated Cellulose Nanofibers (fib-CNF) via Toxicity Tests on Mice: Single Intratracheal Administration and 28 Days Oral Intake. Toxics 12(2): 121.

66. Yang C, Yaqin Zhu, Zhiwei Tian, Chunmei Zhang, Xiaoshuai Han, et al. (2024) Preparation of nanocellulose and its applications in wound dressing: A review, International Journal of Biological Macromolecules 254(Pt 3): 127997.

67. Yang G, Zhikun Zhang, Kefeng Liu, Xingxiang Ji, Pedram Fatehi, et al. (2022) A cellulose nanofibril-reinforced hydrogel with robust mechanical, self-healing, pH-responsive and antibacterial characteristics for wound dressing applications, Journal of Nanobiotechnology 20(1): 312.

68. Yu G, Wu Wu, Jianyang Shi, Lisha Jiang, Haibo Wang, et al. (2025) Conductive and Antibacterial Hydrogel Based on Bacterial Cellulose@ Cu NPs for Accelerated Diabetic Wound Healing and Health Monitoring, ACS Applied Materials & Interfaces 17(45): 61905-61918.

69. Zaini LH (2024) Nanofibrils from oil palm trunk: effect of delignification and fibrillation technique, Journal of Wood Science 70: 19.

70. Zarepour A, Bahar Gok, Yasemin Budama Kilinc, Arezoo Khosravi, Siavash Iravani, et al. (2024) Bacterial nanocelluloses as sustainable biomaterials for advanced wound healing and dressings, Journal of Materials Chemistry B 12(48): 12489-12507.

71. Zattarin E, Zeljana Sotra, Emanuel Wiman, Yagmur Bas, Jonathan Rakar, et al. (2025) Controlled release of antimicrobial peptides from nanocellulose wound dressings for treatment of wound infections, Materials Today Bio 32: 101756.

72. Zattarin E, Wasihun Bekele Kebede, Zeljana Sotra, Rozalin Shamasha, Annika Starkenberg, et al. (2026) Enzyme responsive antimicrobial hyaluronan-nanocellulose hybrid wound dressings for the treatment of infected wounds, Bioactive Materials 61: 150-171.

73. Zhang L (2026) Advances in nanocellulose hydrogels for wound dressing and healing therapy: a review, Materials & Design 268: 116446.

74. Zhang S, Blessing Gatsi, Xue Yao, Yang Jin, Hanane Amhal, et al. (2025) Cellulose nanofiber-reinforced antimicrobial and antioxidant multifunctional hydrogel with self-healing, adhesion for enhanced

wound healing, Carbohydrate Polymers 352: 123189.

75. Zhao S, Wei Zhao, Nan Wang, Junhong Ling, Xiao, Kun Ouyang, et al. (2025) A sustained H2S-releasing nanocellulose-based hydrogel with anti-inflammatory and antibacterial properties for promoting infected wound healing, Carbohydrate Polymers 355: 123424.

76. Zulnazri Z, Rozanna Dewi, Agam Muarif, Ahmad Fikri, Herman Fithra, et al. (2024) Effect of Hydrochloric Acid Hydrolysis under Sonication and Hydrothermal Process to Produce Cellulose Nanocrystals from Oil Palm Empty Fruit Bunch (OPEFB), Polymers 16(13): 1866.