

A sustainable approach to converting biowaste into functional nano-wound dressings

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Abstract: Skin tissue regeneration requires wound dressing materials that are mechanically stable, highly absorbent, and biocompatible. Natural biopolymers derived from renewable and waste resources offer a sustainable approach to developing advanced nano-wound materials with enhanced healing performance. Nano-wound materials (NWMs) were fabricated using cellulose nanocrystals (CNCs), nanofibrin (NF), and chitosan nanoparticles (CNPs) through a film-casting technique. The developed NWMs were characterized using high-resolution scanning electron microscopy (HRSEM). Mechanical properties, water absorption capacity, and biocompatibility were evaluated, with cytocompatibility assessed using MTT assays on NIH/3T3 fibroblast cells. The NWMs exhibited excellent mechanical and physicochemical properties, with a tensile strength of 27.78 ± 0.46 MPa, elongation at break of $31.75 \pm 0.64\%$, flexibility of $8.97 \pm 0.91\%$, and water absorption of $45.71 \pm 0.74\%$. Biocompatibility studies demonstrated high cytocompatibility, with approximately 98% cell viability observed in NIH/3T3 cells. The developed nano-wound materials demonstrated robust mechanical performance and excellent biocompatibility, indicating their suitability for skin wound-healing applications. Additionally, this study highlights a value-added and sustainable strategy for converting fish and slaughterhouse waste into functional, high-performance wound care materials.

Keywords: Green product, Innovative, Medicine, Nanoparticles, Wound dressing.

1. Introduction

Microfibers smaller than 100 nm in diameter, produced by physical and chemical means from natural fibers, are referred to as nanocellulose. They typically range in length from a few micrometers to many tens of nanometers. Common plant-based sources include cotton, bamboo, straw, chestnut, hyacinth, wood, bagasse, corn husk, and wormwood. The size and characteristics of nanocellulose are influenced by its source material [1]. For instance, nanocellulose derived from cotton, wood, or microcrystalline cellulose typically exhibits widths of 5–10 nm and lengths of 100–300 nm, with strong crystallinity, whereas that obtained from bacterial or tunicate fibers has a broader size range (5–60 nm in width and several micrometers in length) [2].

Nanocellulose is extensively investigated for biomedical applications due to its high flexibility, biocompatibility, and biodegradability. It is suitable for use in stents, drug delivery systems, wound dressings, and artificial blood vessels. It is especially effective as a wound dressing because of its high liquid absorption capacity, ability to maintain a moist environment, and nontoxicity, all of which promote optimal wound healing. The morphology of nanocellulose significantly influences its physicochemical behavior and, consequently, determines its efficacy in wound healing applications [3].

Fibrin is a fibrous and viscoelastic protein widely used in surgical practice for hemostasis and tissue repair. As a biodegradable and biocompatible polymer, fibrin provides an ideal matrix for stem cell growth and tissue regeneration. In some Indian slaughterhouses, bovine blood is collected for pharmaceutical use,

and physiologically clotted fibrin (PF), a by-product of this process, is both biocompatible and biodegradable [4]. Chitosan nanoparticles (CNPs) have also emerged as promising wound-dressing materials due to their excellent antimicrobial activity, biodegradability, and biocompatibility. When incorporated into wound-healing matrices, they support rapid healing, reduce local inflammation, and help maintain an optimal moist environment [5].

The purpose of this study was to develop and evaluate novel nanowound materials (NWMs) composed of cellulose nanocrystals (CNCs), nanofibrin (NF), and chitosan nanoparticles (CNPs) for potential use in skin tissue regeneration. The investigators hypothesized that integrating NF and CNPs into a CNC-based matrix would enhance the mechanical properties, water absorption capacity, and biocompatibility of the wound dressing, resulting in improved suitability for chronic wound healing. The specific aims of the study were: (1) to fabricate and characterize different NWM formulations: CNC alone, CNC with NF, and CNC with NF/CNPs; (2) to evaluate their physicochemical properties, including molecular interactions, thermal stability, microstructure, and mechanical strength; and (3) to assess water absorption behavior, biocompatibility, and in vitro biocompatibility using fibroblast cell viability assays.

2. Materials and Method

Cellulose pulp was obtained from Vechem Organics Pvt. Ltd., Chennai, India, and processed by cutting and shredding. Chitosan, sulfuric acid (H_2SO_4), and ammonium persulfate (APS; $(\text{NH}_4)_2\text{S}_2\text{O}_8$) were procured from Sigma-Aldrich (Chennai, India), and all reagents used were of laboratory grade, without further purification. Fresh bovine blood was aseptically collected from the municipal slaughterhouse in Kumananchavadi, Chennai. Platelet fibrin (PF) was extracted by stirring the blood with a glass rod, followed by thorough washing with cold distilled water. It was then treated with 0.5 M sodium acetate and 30% hydrogen peroxide, rewashed, pulverized using a blender, and stored at -20°C until further use. NIH 3T3 fibroblast cells were obtained from the National Centre for Cell Science (NCCS), Pune, India, and cultured in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum at 37°C in a humidified atmosphere containing 5% CO_2 . All chemicals used in this study were of analytical grade.

2.1. Preparation of cellulose Nanocrystals (CNCs)

Cellulose pulp was hydrolyzed using a 60 wt% sulfuric acid solution at a solid-to-liquid ratio of 1:20 (w/w) and maintained at 50°C with continuous stirring for 90 minutes. To terminate the reaction, deionized water was added, and the mixture was centrifuged at 12,000 rpm for 10 minutes to remove residual acid and reducing sugars. This centrifugation step was repeated several times to ensure thorough washing. The resulting precipitate was then dialyzed against ultrapure water for several days until a stable pH was achieved. Following dialysis, the suspension underwent a 30-minute ultrasonic treatment and was centrifuged once more. The supernatant was then adjusted to a 1 wt% concentration and freeze-dried to yield powdered cellulose nanocrystals (CNCs) for further characterization [6].

2.2. Preparation of NanoFibrin (NF)

Nanofibrin (NF) was prepared by dissolving 200 mg of fibrin in 10 mL of 1 N sodium hydroxide (NaOH), resulting in a clear yellow solution. Dilute hydrochloric acid (1 N) was then added dropwise under vigorous stirring at 2000 rpm until the pH reached 5.5, leading to the formation of NF, as indicated by the appearance of a milky white suspension. The resulting NF was transferred into a dialysis bag (molecular weight cutoff: 12,000 Da) and dialyzed against deionized water for 24 h. After dialysis, the NF was lyophilized and stored at 20°C for further use [7].

2.3. Preparation of Chitosan Nanoparticles (CNPs)

A total of 500 mg of chitosan was dissolved in 50 mL of 1% acetic acid and stirred at 1000 rpm for 25 min at room temperature until a clear solution was obtained. This solution was then sonicated and titrated

with either NaOH or HCl to adjust the pH to 5, followed by filtration through a 0.2 μm mesh. For the coating process, 5 mL of the nanomagnetic solution was added to 75 mL of deionized water and sonicated for 10 min. Subsequently, the chitosan solution was added and further sonicated for 5 min, resulting in a clear final solution [8].

2.4. Preparation of Nano Wound Materials (NWMs)

The NWM fabrication process is illustrated in Figure 1. To prepare the nano-wound material (NWM), a 1% chitosan solution in 1% acetic acid was concentrated to 2% using microwave irradiation to remove excess water. Once cooled to room temperature, the gel was mixed using an overhead stirrer for 10 min. Separately, NF and CNP powders were accurately weighed and blended with 10% (w/v) ethanol to form a uniform paste. This paste was then incorporated into the chitosan solution and thoroughly homogenized. The resulting mixture was sonicated using an Elmasonic S40 (H) ultrasonic cleaner for 1 h to eliminate air bubbles. The degassed mixture was poured into 5×5 cm Poly-Cons® plastic molds, frozen at -80°C , and subsequently freeze-dried for 48 h to obtain the final scaffold sheets.

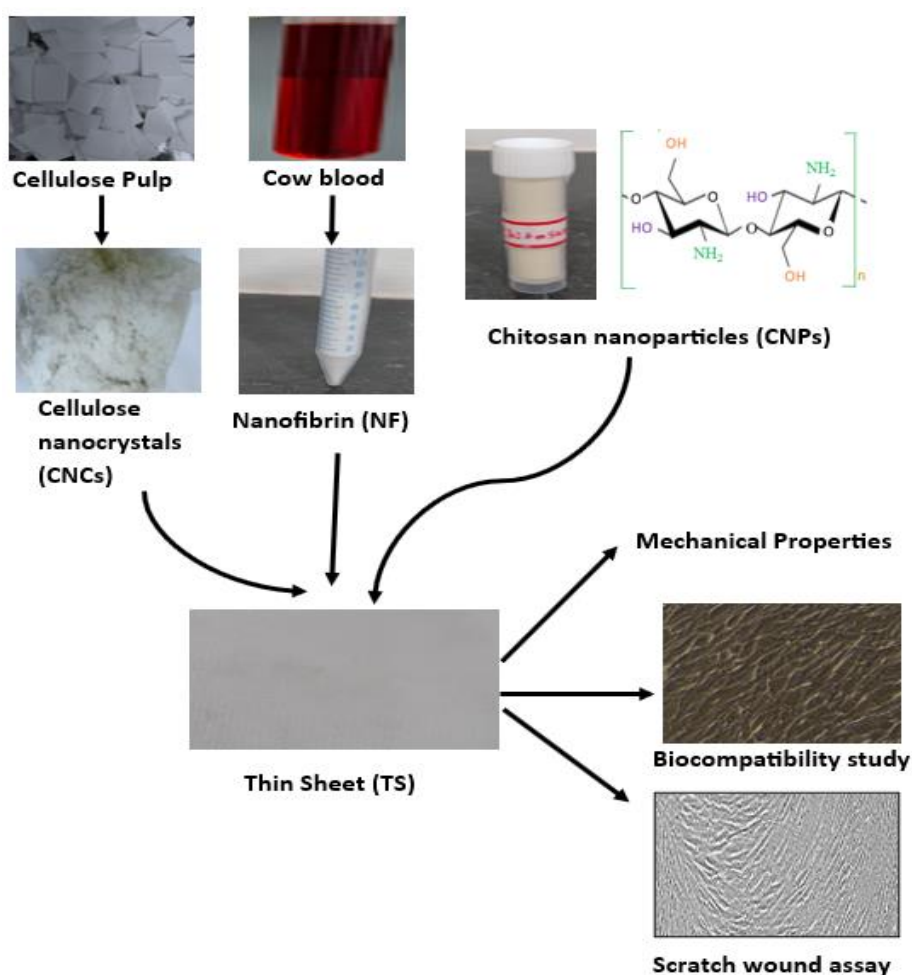


Figure 1.
Preparation of Nano-wound Materials (NWMs)- Schematic Diagram.

2.5. Characterization

The mechanical properties, including tensile strength (MPa) and elongation at break (%), were assessed using an Instron Model 1405 universal testing machine at a crosshead speed of 5 mm/min. Testing was carried out on three dumbbell-shaped specimens (4 mm wide, 10 mm long) under standard tropical conditions (27 °C, 65% RH), according to the ISO/DIS 2419 guidelines. Surface morphology and elemental composition were examined via high-resolution scanning electron microscopy (HRSEM) using a Thermo Scientific Apreo S (Scan 440), with gold sputter coating and imaging performed at an accelerating voltage of 15 kV.

NIH/3T3 fibroblast cells, obtained from the National Center for Cell Sciences (NCCS), Pune, India, were cultured in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and maintained at 37 °C in a humidified atmosphere containing 5% CO₂. Cell viability was determined using the MTT assay, which measures metabolic activity. Cells were seeded at a density of 25×10^3 cells/mL onto the test samples in 24-well plates, followed by the addition of 10% medium after 30 minutes. After incubation for 1 and 5 days, MTT reagent was added, and the cells were further incubated for 4 hours at 37 °C. The formed formazan crystals were solubilized in dimethyl sulfoxide, and absorbance was recorded at 570 nm using a SpectraMax M4 spectrophotometer. Control cells were cultured without test samples, and viability was expressed as a percentage relative to the control. Cell morphology was also examined under a phase-contrast microscope [9].

Enzymatic biodegradation of cellulose-based wound dressing materials can be assessed by incubating the samples in a buffered solution containing cellulase enzyme (typically from *Trichoderma reesei*) at 37 °C to simulate physiological conditions. Degradation is monitored at specific time intervals by measuring weight loss [10].

3. Results and Discussion

3.1. Surface Analysis of CNCs, NF, and CNPs

The HRSEM images of CNCs, NF, and CNPs (Figure 2A–C) display their distinct morphological features. CNCs exhibited a uniform rod-like structure with smooth surfaces and minimal agglomeration, and particle diameters ranged from 10 to 50 nm, aligning with typical nanoscale cellulose reported in earlier studies. NF particles appeared as circular nanostructures, with sizes ranging from 80 ± 20 to 120 ± 30 nm, consistent with previously published data on human fibrin network architecture. CNPs showed a spherical morphology with a uniform distribution, supporting their suitability as polymeric carriers for therapeutic applications. Their defined nanoscale size and structure contribute to enhanced drug-delivery performance, including targeted biodistribution, reduced systemic toxicity, and improved therapeutic efficacy.

The HRSEM analysis of CNCs, NF, and CNPs confirmed their nanoscale morphology and structural integrity, closely aligning with previously reported literature. The rod-like morphology of CNCs, with diameters ranging from 10 to 50 nm, is consistent with the findings of Whba, et al. [11], who demonstrated that sulfuric acid-hydrolyzed CNCs exhibit high aspect ratios and smooth surfaces conducive to reinforcing polymer matrices. The NF particles, with diameters between 80 ± 20 and 120 ± 30 nm, correlate with a study by Risser, et al. [12], which documented the nanoscale arrangement and dense fiber networks of physiologically derived fibrin. The spherical CNPs observed in this study reflect morphologies previously reported by Zhao, et al. [13], highlighting chitosan's ability to form stable, uniform nanoparticles ideal for biomedical applications. These morphological features, verified through HRSEM, underscore the potential of these materials for wound-healing applications, where nanoscale architecture plays a critical role in cellular interactions, bioactivity, and therapeutic performance.

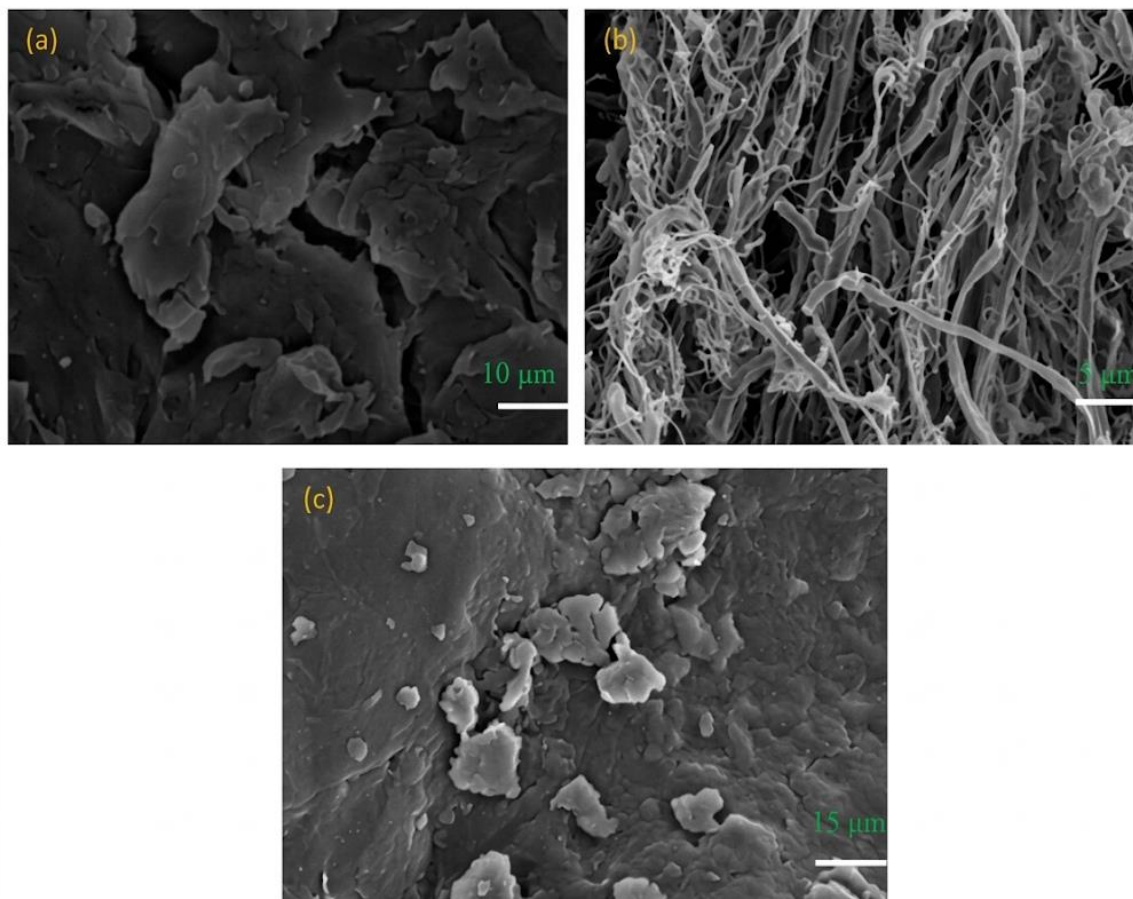


Figure 2.
(A) HRSEM of CNCs, (B) HRSEM of NF, (C) HRSEM of CNPs.

3.2. Physicochemical Characterization of Nano-Wound Materials (NWMs)

Figure 2A illustrates the FTIR spectra of NWMs, where the peak at 1700 cm^{-1} confirms the presence of acetyl groups from hemicellulose in CNF. The broad peak at 3445 cm^{-1} corresponds to O–H stretching vibrations, while the peak at 1638 cm^{-1} is attributed to carboxylic group vibrations. Additional peaks at 1058 , 1378 , and 1608 cm^{-1} represent C–O–C stretching, C–O–H bending, and C=C stretching of the sp^2 carbon backbone, respectively, indicating the successful integration of CNF, chitosan biopolymer (CBP), and reduced graphene oxide (r-GO) within the matrix. The incorporation of r-GO improved the structural integrity and packing density of the starch-based nanocomposite, thereby enhancing its tensile properties. As shown in Fig. 3b, TGA analysis revealed a two-stage degradation pattern: an initial mass loss between 34.80 and $152.18\text{ }^{\circ}\text{C}$ due to moisture evaporation (7.49%), followed by the decomposition of CNCs, NF, and CNPs in the range of 250 – $350\text{ }^{\circ}\text{C}$, with a major weight loss of around 52%. HRSEM images (Fig. 3c) showed a uniformly distributed and compact nanosheet morphology, attributed to r-GO reinforcement and the formation of an interconnected matrix that supports the structural cohesiveness of NWMs. HRSEM images (Figure 2B) showed a uniformly distributed and compact nanosheet morphology, attributed to r-GO reinforcement and the formation of an interconnected matrix that supports the structural cohesiveness of NWMs.

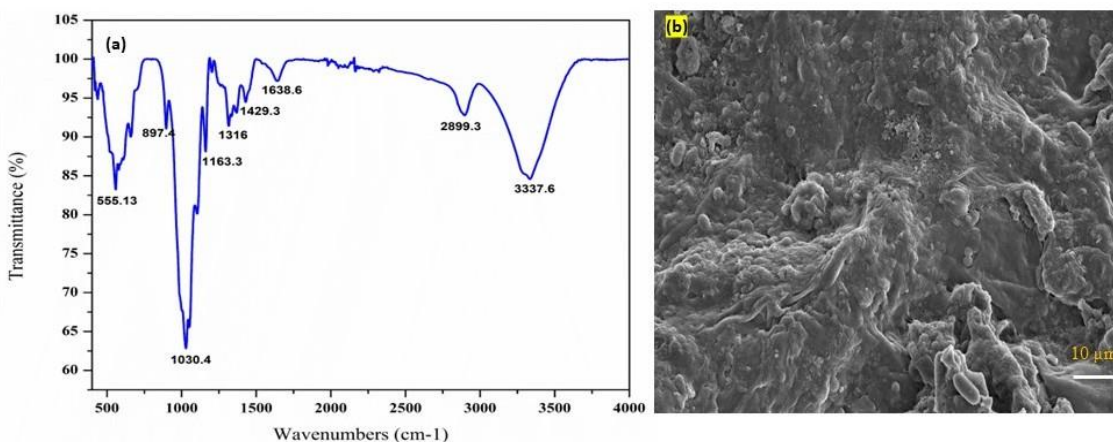


Figure 3.
(A) FTIR spectrum of CNCs-NF-CNPs; (B) HRSEM image of CNCs-NF-CNPs.

The developed nano-wound materials (NWMs), composed of CNCs, NF, and CNPs, demonstrated favorable physicochemical characteristics, including good water absorption and uniform nanoscale morphology, which are critical for wound-healing applications. These findings are consistent with earlier studies by Noor-ul-Ain, et al. [14], who reported enhanced mechanical integrity and biocompatibility in CNC-based scaffolds when blended with biopolymers. Similarly, the incorporation of fibrin-derived nanofibers has been shown to promote cellular adhesion and proliferation due to their native protein structure, as highlighted in the work of Li, et al. [15]. Chitosan nanoparticles, known for their antibacterial and hemostatic properties, have also been widely used in wound-care materials to support tissue regeneration, as demonstrated by Kim, et al. [16]. The synergistic integration of these components in the current study not only supports their functional roles but also enhances the overall wound-dressing performance, aligning well with previous literature on multifunctional nanocomposite systems for chronic wound management.

3.3. Mechanical Properties

The mechanical properties of CNCs, CNCs-NF, and CNCs-NF-CNPs, as presented in Table 1, revealed that the CNCs-NF-CNPs formulation exhibited superior tensile strength, elongation at break, flexibility, and water absorption capacity compared with the other groups. The water absorption behavior of the wound-dressing materials plays a vital role in their application as wound dressings by aiding moisture retention and minimizing microbial proliferation. Although CNCs alone demonstrated higher water uptake, the inclusion of NF and CNPs slightly reduced this property, likely because the collagen content in these components contributed to a more compact matrix structure and reduced porosity.

The improved mechanical strength and water absorption behavior observed in the CNCs-NF-CNPs formulation align with previous studies highlighting the synergistic effects of nanofibrin and chitosan nanoparticles when integrated into biopolymeric matrices. For instance, Janmohammadi, et al. [17] demonstrated that incorporating chitosan nanoparticles enhanced the tensile strength and elasticity of cellulose-based composites through increased interfacial bonding and network density. Similarly, the proteinaceous nature and intrinsic bioactivity of fibrin contribute not only to structural integrity but also to enhanced cell proliferation and wound healing, as reported by Weisel and Litvinov [18]. The balanced water absorption observed in CNCs-NF-CNPs indicates a controlled, moisture-retentive environment, which is critical for wound healing. Maintaining a moist wound environment facilitates autolytic debridement, reduces pain, activates collagen synthesis, and supports the presence and function of growth factors and other soluble mediators in the wound microenvironment. Additionally, hydrogels, known for their high water content (70–90%), effectively absorb exudates and maintain a moist environment

conductive to healing. These findings underscore the importance of moderate water uptake in wound dressings for promoting optimal healing conditions [19]. These results support the potential of CNCs-NF-CNPs as an effective material for chronic wound care applications.

Table 1.

Mechanical properties of CNCs, CNCs-NF, and CNCs-NF-CNPs.

Samples	Tensile strength (Mpa)	Elongation at break (%)	Flexing index (%)	Water absorption (%)
CNCs	18.91±0.76	20.56±0.64	5.76±0.67	39.73±0.23*
CNCs-NF	21.61±0.35*	25.67±0.87	6.36±0.57*	41.86±0.51
CNCs-NF-CNPs	27.78 ± 0.46	31.75 ± 0.64*	8.97 ± 0.91	45.71 ± 0.74

Note: The data are presented as the mean ± SD of three individual experiments.

*p < 0.05. Compared to CNCs, using Duncan's multiple range analysis.

3.4. Cell Viability

Biocompatibility assessments (Figure 3A) indicated that both CNCs-NF-CNPs and the control group exhibited no cytotoxic effects on NIH/3T3 cells after 12, 24, and 72 h of exposure. At 12 h, CNCs-NF-CNPs maintained cell viability ranging from 64–71%, which increased to 84% at 24 h, suggesting initial adaptation followed by proliferation. Notably, after 72 h, cell viability further increased to 98%, indicating excellent cellular tolerance and compatibility, particularly with the Gel: Nano-FB formulation. The gradual increase in cell viability after 24 h signifies active cell proliferation and scaffold support. Phase-contrast microscopy confirmed that NIH/3T3 cells adhered well to the CNCs-NF-CNPs surface, with morphology comparable to that of the control group (Figure 3B).

The biocompatibility of CNCs-NF-CNPs was demonstrated by the progressive increase in NIH/3T3 cell viability over 72 h, aligning with earlier studies that reported favorable cellular responses to chitosan- and fibrin-based composites because of their natural origin and bioactive properties [20]. The presence of nanocellulose and fibrin promotes a conducive microenvironment for cell adhesion and proliferation, while chitosan nanoparticles have been shown to enhance scaffold stability and reduce cytotoxicity [21]. The final viability rate of 97% after 72 h indicates excellent scaffold–cell interaction, corroborating the findings of Li, et al. [15], who observed similar results with fibrin-incorporated biopolymers for tissue engineering applications. These outcomes confirm the potential of CNCs-NF-CNPs as a promising, biocompatible platform for wound healing and regenerative medicine.

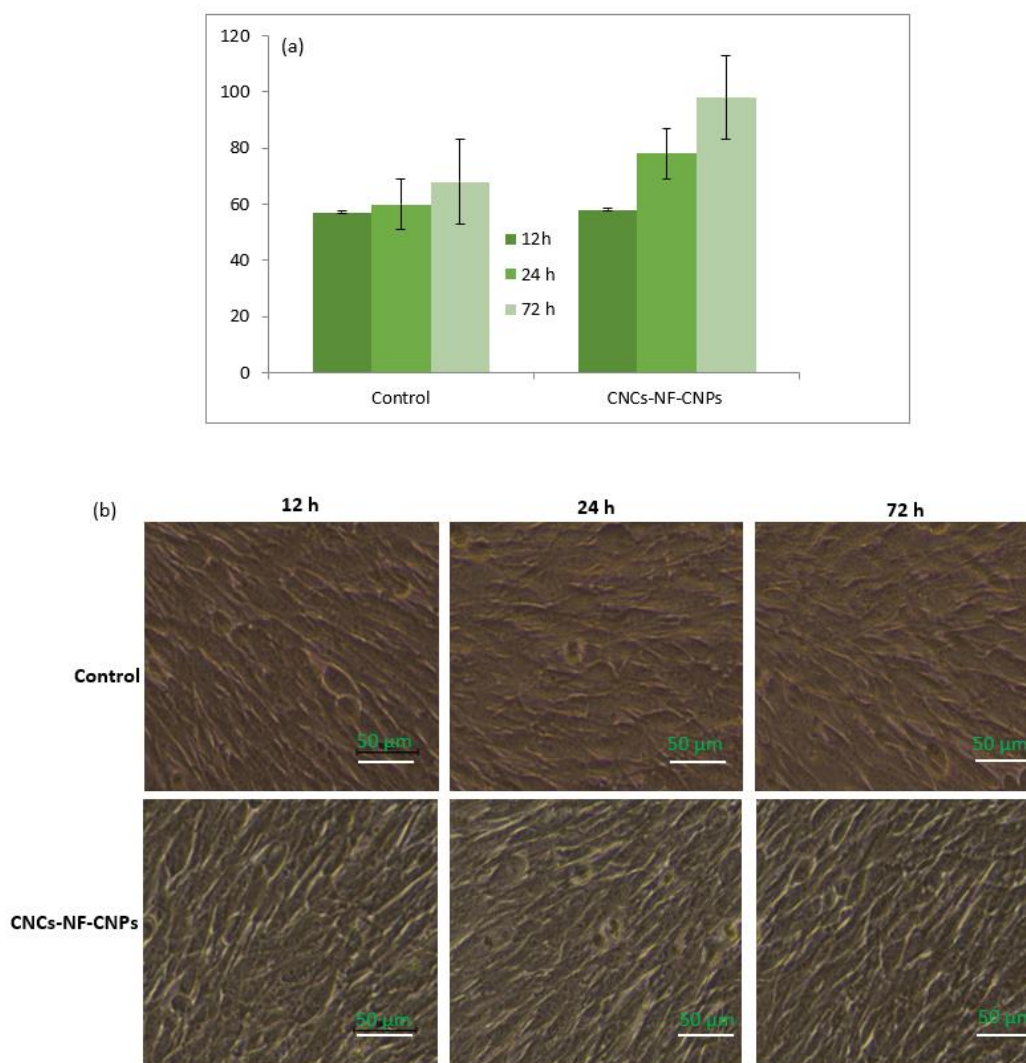


Figure 4. (A) MTT assay of the control sample and CNCs-NF-CNPs on NIH/3T3 cells; (B) Phase-contrast micrographs (30X) of NIH/3T3 cells cultured at 12, 24, and 72 h.

3.5. Biodegradation Study

Biodegradation studies are crucial for wound dressing materials to ensure that they safely break down in the body without causing toxicity or inflammation. They help determine the material's stability, degradation rate, and compatibility with the healing process. This ensures that the dressing supports tissue regeneration and is gradually resorbed as the wound heals. Hence, the development of nanofibrous wound materials (NWMs) is imperative. The biodegradation behavior of CNCs, CNCs-NF, and CNCs-NF-CNPs is illustrated in Figure 4. Among them, CNCs-NF-CNPs, which exhibited superior mechanical strength, were selected for enzymatic degradation analysis. After 20 days, CNCs-NF-CNPs showed an approximately 98% weight loss, indicating significant biodegradability.

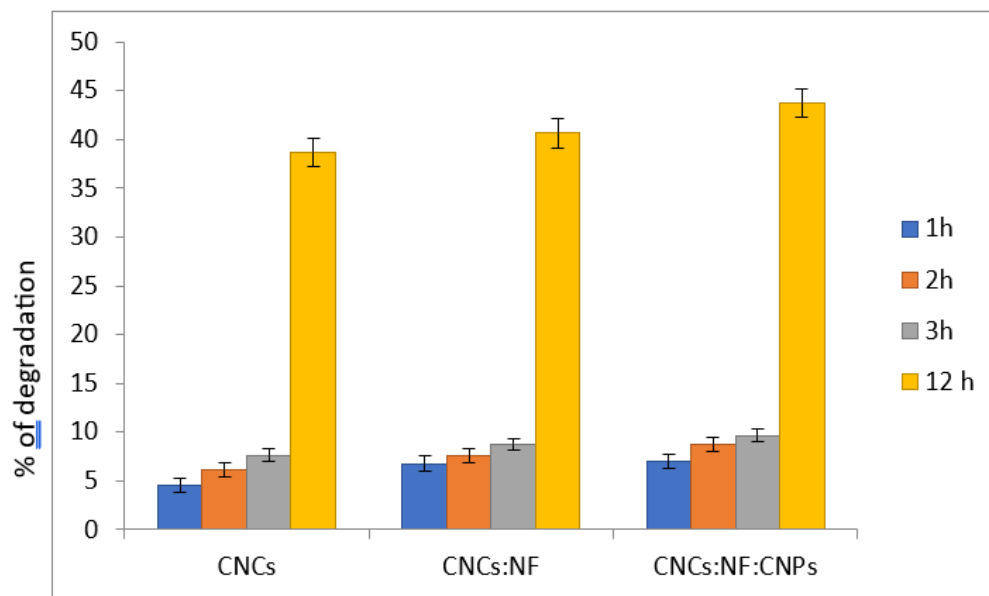


Figure 5.
Enzymatic degradation of CNCs, CNCs-NF, and CNCs-NF-CNPs.

The enzymatic biodegradation profile of CNCs-NF-CNPs revealed a substantial weight loss of 92% over 20 days, highlighting their potential as biodegradable wound dressing materials. This finding aligns with previous studies, such as that by Lu, et al. [22] who demonstrated that cellulose nanocomposite scaffolds showed over 80% degradation within three weeks under cellulase activity [23]. Similarly, Oliver-Cuenca, et al. [24] reported that the incorporation of nanoparticles, such as chitosan or metal oxides, did not significantly hinder enzymatic degradation but instead enhanced material performance. The rapid degradation observed in CNCs-NF-CNPs may be attributed to the porous nanofibrous structure and the presence of bioactive CNPs, which facilitate enzyme penetration and substrate accessibility. This supports their suitability for temporary wound coverage, offering both mechanical support and timely bioresorption during the healing process.

The present study demonstrated that the developed nano-wound materials (NWMs), composed of cellulose nanocrystals (CNCs), nanofibrin (NF), and chitosan nanoparticles (CNPs), exhibited favorable mechanical strength, water absorption, and excellent biocompatibility, making them suitable candidates for skin tissue regeneration. The tensile strength and flexibility values fall within the desirable range reported for biomaterials intended for wound-dressing applications. Furthermore, the high cell viability (89%) observed in MTT assays is consistent with prior findings on chitosan- and fibrin-based scaffolds, which have shown minimal cytotoxicity and supported fibroblast proliferation. The observed delay in wound closure in the presence of cortisol confirms earlier reports on the negative impact of stress hormones on tissue-repair processes. The integration of biopolymers from fish and slaughterhouse waste introduces a sustainable, value-added approach to wound care, echoing recent trends in the use of bio-based and waste-derived materials for biomedical applications. Overall, the findings support the potential of NWMs as eco-friendly and effective solutions for enhancing wound-healing outcomes.

Similarly, Sangeetha, et al. [25] demonstrated the cytocompatibility and regenerative potential of electrospun chitosan/polyvinyl alcohol/montmorillonite clay scaffolds, underscoring their applicability in skin tissue engineering. Complementing these findings, Gomez Mesa, et al. [26] reviewed various nanocomposites and their innovative contributions to skin tissue repair, highlighting their multifunctionality, including antimicrobial activity, enhanced healing rates, and structural mimicry of native extracellular matrices. Together, these studies reflect the emerging trend of utilizing

nanostructured and bioactive composites to create next-generation wound dressings with multifunctional capabilities. The high cytocompatibility and enhanced fibroblast proliferation observed in the present nano-wound materials are consistent with earlier reports on chitosan-based electrospun scaffolds, which demonstrated excellent cell viability and skin regeneration potential through favorable polymer–cell interactions [27]. Similarly, the biocompatible behavior of chitosan nanostructures reported by Mustafa, et al. [28] supports the role of chitosan-derived nanomaterials in promoting cellular responses, reinforcing the suitability of the developed NWMs for regenerative biomedical applications.

The excellent performance of the developed nano-wound materials (CNCs-NF-CNPs) can be attributed to the synergistic interactions among cellulose nanocrystals, nanofibrin, and chitosan nanoparticles. Rather than functioning independently, each component contributes complementary physicochemical and biological properties that collectively enhance the composite's wound-healing potential. Cellulose nanocrystals provide a mechanically robust framework with high crystallinity, enabling the scaffold to withstand handling during dressing application while maintaining structural integrity under physiological conditions. The incorporation of nanofibrin introduces biologically active protein domains that resemble the native extracellular matrix, facilitating fibroblast attachment, migration, and proliferation [22]. Chitosan nanoparticles further improve the composite by contributing antimicrobial activity, biocompatibility, and moisture retention, all of which are essential characteristics of an ideal wound dressing.

One of the most significant findings of the present study is the balanced relationship between mechanical strength and water absorption. Although highly absorbent dressings effectively manage wound exudate, excessive swelling may compromise their structural stability and reduce patient comfort [29]. The CNCs-NF-CNPs formulation demonstrated an optimal level of water absorption while maintaining superior tensile strength and flexibility, suggesting that the material can preserve a moist wound environment without losing its mechanical performance. Such characteristics are particularly advantageous for chronic wounds, diabetic ulcers, pressure ulcers, and burn injuries, where prolonged moisture management and mechanical durability are essential for successful tissue repair.

The remarkable cytocompatibility observed in NIH/3T3 fibroblast cells further supports the biological safety of the developed scaffold. The progressive increase in cell viability over the incubation period indicates that the material not only lacks cytotoxic effects but also actively supports cellular proliferation. This favorable cellular response may result from the natural origin of all three biomaterials, which provide abundant hydroxyl, amino, and peptide functional groups that promote protein adsorption and cell–material interactions [30]. Enhanced fibroblast proliferation is a critical event during the proliferative phase of wound healing because these cells are responsible for extracellular matrix synthesis, collagen deposition, angiogenic signaling, and tissue remodeling. Therefore, the developed nano-wound material provides an appropriate microenvironment for regenerative processes rather than merely serving as a passive wound covering. Recent studies have highlighted the potential of chitosan-based biomaterials in wound healing. Sivalingam, et al. [31] developed a cross-linker-free chitosan/strontium bioglass composite with promising healing properties, while Murali, et al. [32] emphasized nanostructured chitosan scaffolds for enhanced diabetic wound management and tissue regeneration.

Another noteworthy aspect of this investigation is its contribution to sustainable biomedical material development. The utilization of cellulose from renewable resources, together with fibrin recovered from slaughterhouse by-products, demonstrates an environmentally responsible strategy for producing high-value medical biomaterials from biological waste streams. This circular bioeconomy approach reduces the environmental burden while simultaneously lowering raw material costs associated with conventional wound dressing production. Such sustainable manufacturing strategies are increasingly encouraged because they combine environmental conservation with biomedical innovation, thereby improving both economic feasibility and clinical accessibility.

Despite these encouraging findings, certain limitations should be acknowledged. The present investigation primarily evaluated the physicochemical characteristics, biodegradation behavior, and in vitro cytocompatibility of the nanowound materials. Additional investigations involving antimicrobial

efficacy against wound pathogens, hemocompatibility, inflammatory cytokine regulation, oxidative stress analysis, and in vivo wound-healing studies are necessary to comprehensively validate the therapeutic performance of the developed scaffold. Furthermore, long-term storage stability, sterilization compatibility, and large-scale manufacturing processes should also be investigated before clinical translation. Nevertheless, the favorable mechanical properties, excellent biodegradability, high fibroblast compatibility, and sustainable origin collectively demonstrate that CNCs-NF-CNPs represent a promising next-generation biomaterial for advanced wound management and skin-tissue regeneration, providing a strong foundation for future preclinical and clinical investigations.

4. Conclusion

In this study, NWMs were successfully developed as promising wound-dressing materials with notable commercial potential. The fabricated NWMs exhibited excellent biodegradability, biocompatibility, adequate tensile strength, and flexibility, key properties for effective wound care. Various characterization techniques confirmed the improved performance of the NWM-based films, supporting their potential application in tissue regeneration and healing. These findings highlight the suitability of NWMs for promoting wound recovery. Future investigations will aim to evaluate the therapeutic efficacy of NWMs in animal models before potential clinical application in humans.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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