

# XEROPHYTIC NANOCELLULOSE: A PLATFORM LINKING SMART DRUG DELIVERY, TISSUE ENGINEERING, AND SUSTAINABLE CONSTRUCTION

Paulo Roberto Ramos<sup>1</sup>

Rodrigo Almeida Ferreira<sup>2</sup>

Luzineide Dourado Carvalho<sup>3</sup>

Cleyton de Almeida Araújo<sup>4</sup>

Sidclay Cordeiro Pereira<sup>5</sup>

Gustavo Frensch<sup>6</sup>

Rubens Silva Carvalho<sup>7</sup>

Beatriz Lemos Cavalcante de Carvalho Santiago<sup>8</sup>

Airton de Deus Cysneiros Cavalcanti<sup>9</sup>

Lícia Mara Marinho da Silva<sup>10</sup>

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1 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: paulo.ramos@univasf.edu.br – Orcid: <https://orcid.org/0000-0003-3684-0960>

2 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: rodrigo.almeida@discen-te.univasf.edu.br. Orcid: <https://orcid.org/0009-0006-2981-080X>

3 Universidade do Estado da Bahia (UNEB)- E-mail: luzdourado-13@hotmail.com - Orcid: <https://orcid.org/0009-0006-9096-2415>

4 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: cleyton.araujo@univasf.edu.br. Orcid: <https://orcid.org/0000-0003-3636-2890>

5 Universidade de Pernambuco (UPE). E-mail: sidclay.pereira@upe.br. Orcid: <https://orcid.org/0000-0002-4916-8969>

6 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: gustavo.frensch@univasf.edu.br. Orcid: <https://orcid.org/0000-0003-2774-4934>

7 Universidade do Estado da Bahia (UNEB)- E-mail: E-mail rscarvalho@uneb.br - Orcid: <https://orcid.org/0000-0002-7392-7224>

8 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: beatriz.lemos@univasf.edu.br. Orcid: <https://orcid.org/0000-0002-6306-4832>.

9 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: airton.cavalcanti@univasf.edu.br. Orcid: <https://orcid.org/0000-0001-6626-9852>

10 Empresa Brasileira de Pesquisa Agropecuária (Embrapa). E-mail: E-mail:licia.marinho@embrapa.br. Orcid: <https://orcid.org/0009-0002-2822-9256>

Carlos Gomes de Lima<sup>11</sup>  
Mariana Santana de Jesus<sup>12</sup>  
Edmo Henrique Martins Cavalcante<sup>13</sup>  
Cristiana de Sousa Alves Paes Landim<sup>14</sup>  
Pedro Paulo da Cunha<sup>15</sup>  
Adson Cardoso de França<sup>16</sup>  
Antônio Fernando Barros da Silva Junior<sup>17</sup>  
Neemias da Silva Souza<sup>18</sup>  
Maria Miryam da Silva Alves<sup>19</sup>

**Abstract:** The increasing demand for sustainable materials has intensified the search for alternatives to synthetic polymers, particularly in applications requiring both mechanical and biological performance. In this context, nanocellulose has emerged as a promising platform, although gaps remain in integrating its structural properties with multifunctional applications, especially when derived from xerophytic plants. This study aimed to analyze the physicochemical, mechanical, and biological properties of

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11 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: engomes2017@gmail.com. Orcid: <https://orcid.org/0009-0007-5727-8889>

12 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: jesusmarianasantana@hotmail.com. Orcid: <https://orcid.org/0000-0002-5022-7719>

13 Universidade Federal Rural de Pernambuco (UFRPE). E-mail: edmo.cavalcante@ufrpe.br. Orcid: <https://orcid.org/0000-0003-0509-4475>

14 Faculdade de Venda Nova do Imigrante (FAVENI). E-mail: roprofgeo@gmail.com. Orcid: <https://orcid.org/0009-0001-1180-1757>

15 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: pedro.paulo@discente.univasf.edu.br. Orcid: <https://orcid.org/0009-0006-8010-0862>

16 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: adsoncardoso10@hotmail.com. Orcid: <https://orcid.org/0000-0002-1886-8698>

17 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: antonio.fernandobarros@univasf.edu.br. Orcid: <https://orcid.org/0009-0001-4770-5396>

18 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: neemiassilva2@hotmail.com. Orcid: <https://orcid.org/0000-0001-5275-9850>

19 Universidade Federal do Vale do São Francisco (UNIVASF). E-mail: marymirya@gmail.com. Orcid: <https://orcid.org/0009-0003-7413-5389>

nanocellulose obtained from semi-arid adapted species, focusing on its applications in controlled drug delivery systems and sustainable construction materials. An integrative review was conducted between October 2025 and March 2026, using major scientific databases, yielding 315 initial records, of which 35 comprised the final corpus. The results indicate that high crystallinity, aspect ratio, and hydrophilicity enhance nanocellulose performance as a hydrogel matrix, a responsive drug delivery system, and a reinforcing agent in composites. The discussion highlights a functional convergence between molecular properties and applications, while also revealing disciplinary fragmentation and a lack of studies on Caatinga species. It is concluded that xerophytic nanocellulose represents a platform technology with significant innovation potential, particularly when integrated into sustainable production frameworks.

**Keywords:** Crystallinity. Hydrophilicity. Biomaterials. Composites. Sustainability.

## INTRODUCTION

Escalating environmental impacts associated with petrochemical-based materials have accelerated the search for renewable and biodegradable alternatives. Although synthetic polymers offer structural versatility, their dependence on non-renewable resources and environmental persistence remain critical limitations. In this scenario, lignocellulosic biomass has gained relevance as a sustainable feedstock for advanced materials with improved ecological performance (Gupta; Shukla, 2020; Chaka, 2022).

Recent developments in green chemistry highlight agricultural residues as promising precursors for high-value nanomaterials, yet challenges related to scalability and structural consistency persist across biomass sources (Gandhi et al., 2024; Mateo et al., 2021). Conventional nanomaterials also face constraints such as cytotoxicity and high production costs, restricting broader applications (Patil et al., 2021). At the nanoscale, performance is largely dictated by crystallinity and aspect ratio,

which influence both mechanical strength and biological interactions (Wang et al., 2019; Mariano et al., 2016).

Nanocellulose has emerged as a high-performance bio-based material due to its remarkable mechanical strength, low density, and surface functionality. It occurs primarily as cellulose nanocrystals and cellulose nanofibers, whose structural differences determine their applicability (Chaka, 2022; Patil et al., 2021). Nanocrystals exhibit high crystallinity and stiffness, while nanofibers form flexible, hydrated networks suitable for diverse applications.

Such structural variability enables applications ranging from biomedical scaffolds to structural composites (Wang et al., 2019; Mariano et al., 2016). The relationship between crystallinity and aspect ratio plays a decisive role in reinforcing efficiency and biological performance, with higher aspect ratios improving stress transfer and increased crystallinity enhancing stability (Gupta; Shukla, 2020).

Xerophytic plants remain underexplored despite their potential as nanocellulose sources. The Caatinga biome, marked by water scarcity and intense solar exposure, induces structural adaptations that result in mechanically robust and compact fibers. These characteristics are particularly advantageous for nanomaterial production.

Species such as *Cereus jamacaru* and *Agave sisalana* exhibit fibrous architectures optimized for resilience, and studies with related taxa have demonstrated the feasibility of extracting nanocellulose with favorable crystallinity and morphology (Orrabalis et al., 2019; Rosli et al., 2013). Even so, research on these species remains fragmented, reflecting a persistent gap in the integration of xerophytic biomass into nanotechnology research.

Existing studies frequently address nanocellulose within isolated domains, limiting the understanding of how molecular characteristics translate into multifunctional applications. Connections between ecological origin, nanoscale structure, and technological performance are rarely established. This fragmentation hinders the consolidation of nanocellulose as a fully optimized platform for biomedical and engineering applications.

This study aims to synthesize the physicochemical, mechanical, and biological properties of nanocellulose derived from Caatinga species, particularly *Cereus jamacaru* and *Agave sisalana*, focusing on their applicability in drug delivery systems and sustainable construction materials.

The guiding research question is: What are the physicochemical, mechanical, and biological properties of nanocellulose extracted from Caatinga species that enable its application in controlled drug delivery systems and as reinforcement in sustainable construction materials?

This integrative review seeks to connect molecular properties with applied technologies while advancing the concept of a xerophytic closed-loop biorefinery model.

## **METHODOLOGY**

### **Study Design**

This study was developed as an integrative literature review, a methodological approach particularly suited to the synthesis of heterogeneous evidence and to the articulation of conceptual, empirical, and applied perspectives within a single analytical framework. Unlike narrowly restrictive review models, the integrative review enables the inclusion of studies with distinct methodological designs, thereby supporting a broader and more critical understanding of complex scientific problems. Such flexibility is especially relevant for the present investigation, since nanocellulose derived from xerophytic species must be examined simultaneously as a biomaterial, a biomedical platform, and an engineering reinforcement agent (Torraco, 2005; Mendes; Silveira; Galvão, 2008).

The choice of this design was also justified by the interdisciplinary nature of the research question. The topic under analysis lies at the intersection of materials science, nanotechnology, biomaterials, drug delivery, tissue repair, and sustainable construction. A fragmented reading of the literature would be insufficient to capture how the physicochemical and structural properties of nanocellulose influence its multifunctional performance across these domains.

In this sense, the integrative review was adopted not merely as a strategy for gathering

publications, but as a structured method for comparing evidence, identifying convergences and contradictions, and producing an interpretative synthesis capable of advancing theoretical and technological understanding (Souza; Silva; Carvalho, 2010; Torraco, 2005).

Methodologically, the review followed a rigorous sequence composed of problem identification, definition of the guiding question, establishment of search procedures, application of eligibility criteria, systematic screening of records, extraction of relevant variables, thematic organization of findings, and critical synthesis of the evidence. This procedural orientation is consistent with the classical formulation of integrative reviews in health and applied sciences, particularly when the objective is not only to summarize the state of the art, but also to identify gaps, refine analytical categories, and support conceptual innovation (Mendes; Silveira; Galvão, 2008; Souza; Silva; Carvalho, 2010).

Accordingly, the present review was designed to generate an organized and critical synthesis of the literature on nanocellulose from xerophytic biomass, with emphasis on its structural properties and translational applicability.

To ensure analytical consistency, the study was guided by a prior conceptual delimitation of the object, focusing on nanocellulose extracted from lignocellulosic and xerophytic plant matrices, especially *Cereus jamacaru* and *Agave sisalana*, and on its potential use in controlled drug delivery systems and sustainable construction materials. This delimitation prevented excessive thematic dispersion and enabled the review to remain anchored in a coherent argumentative line, moving from molecular and structural features toward biomedical and engineering applications. As a result, the methodological design was not limited to bibliographic aggregation; it functioned as a mechanism of epistemic integration, allowing dispersed findings to be reorganized into a robust interpretive architecture.

## **Search Strategy and Databases**

The bibliographic search was conducted between October 2025 and March 2026 in four

international databases selected for their relevance to the scientific domains covered by the review: Web of Science, Scopus, PubMed, and ScienceDirect. The choice of these databases was deliberate and complementary. Web of Science and Scopus were used because of their broad coverage of high-impact studies in materials science, polymers, biomaterials, and nanotechnology. PubMed was included to strengthen the retrieval of studies related to wound healing, biocompatibility, drug delivery, and tissue engineering. ScienceDirect was incorporated due to its strong indexing of publications in applied chemistry, materials engineering, composite systems, and sustainable construction. This combination was intended to minimize disciplinary bias and increase the sensitivity of the search process.

The search strategy was organized on the basis of three descriptor groups previously defined according to the PICo logic of the study. The first group referred to the material of interest, including the terms Nanocellulose, Cellulose Nanocrystals, and Cellulose Nanofibers. The second group referred to the biological source, comprising Cactaceae, *Cereus jamacaru*, *Agave sisalana*, and Xerophytic plants. The third group addressed the application domains, including Drug Delivery Systems, Wound Dressings, Biotextiles, Green Construction, and Composite Materials. These descriptors were combined through Boolean operators adapted to the syntax requirements of each database.

The search strings were structured to maximize both specificity and retrieval breadth. In general terms, the strategy followed the logic PICo structure:

- P: Nanocellulose from lignocellulosic and xerophytic plant sources
- I: Physicochemical, mechanical, and biological properties
- Co: Controlled drug delivery systems and sustainable construction materials

From this structure, Boolean combinations were built using the operator OR within descriptor groups and AND between groups, for example: (Nanocellulose OR “Cellulose Nanocrystals” OR “Cellulose Nanofibers”) AND (Cactaceae OR “*Cereus jamacaru*” OR “*Agave sisalana*” OR “Xerophytic plants”) AND (“Drug Delivery Systems” OR “Wound Dressings” OR Biotextiles OR “Green Construction” OR “Composite Materials”).

Whenever necessary, controlled vocabulary terms and indexing variations were incorporated according to the search interface of each database. In addition, filters were applied to restrict results to peer-reviewed articles, review papers, and original investigations whose titles, abstracts, or keywords demonstrated direct relevance to the topic. The time frame of the search reflected the operational stage of the review and not a priori chronological restriction of publication year, since the goal was to retrieve both foundational and recent evidence related to the object of analysis.

The initial database search resulted in 315 records, which constituted the primary corpus subjected to the subsequent stages of screening and eligibility assessment. After retrieval, all references were exported to a bibliographic management system for organization, duplicate checking, and preliminary standardization. At this stage, metadata inconsistencies were corrected, repeated entries were identified, and the records were prepared for title and abstract screening.

Table 1 synthesizes the operational structure of the bibliographic search, detailing the databases consulted, the descriptor combinations employed, the filters applied, and the numerical progression from initial retrieval to final selection. The organization of the search strategy reflects an intentional effort to balance sensitivity and specificity, ensuring that the corpus captured both foundational and application-oriented studies relevant to nanocellulose derived from lignocellulosic and xerophytic sources.

The distribution of descriptors across databases was not uniform, but rather adapted to the indexing logic and disciplinary strengths of each platform. While Web of Science and Scopus concentrated a higher volume of publications in materials science and nanotechnology, PubMed contributed studies with stronger emphasis on biomedical applications. ScienceDirect complemented the dataset with engineering-focused investigations, particularly in the domain of composite materials and sustainable construction.

Table 1. Search Strategy, Databases, and Selection Criteria

Database	Search Keywords (Descriptors)	Filters Applied	Records Retrieved (n)	Records Selected (n)
Web of Science	Nanocellulose; CNC; CNF AND Cactaceae; Cereus jamacaru; Agave sisalana AND Drug Delivery; Composites	Articles; Reviews; English; Peer-reviewed	92	34
Scopus	Nanocellulose; Cellulose Nanofibers AND Xerophytic plants; Agave AND Wound Dressings; Biotextiles	Articles; Reviews; English; Open access where possible	105	41
PubMed	Nanocellulose AND Wound Healing; Drug Delivery; Tissue Engineering	Clinical relevance; Full-text; English	56	22
Science Direct	Nanocellulose AND Composite Materials; Green Construction; Polymer Reinforcement	Research articles; Engineering focus; English	62	26
Total	—	—	315	123

Source: Developed by the authors.

The initial retrieval of 315 records demonstrates the breadth of the topic and confirms the growing scientific interest in nanocellulose across multiple domains. However, the reduction to 123 selected studies after screening highlights a critical issue: a substantial portion of the literature does not meet the integrative criteria required to connect molecular properties with applied functionalities. This discrepancy reinforces the fragmented nature of current research, in which studies often remain confined to isolated disciplinary perspectives.

A closer examination of the distribution reveals that Scopus and Web of Science together accounted for the majority of selected studies, indicating their central role in disseminating high-impact research on nanocellulose. In contrast, PubMed, despite retrieving fewer records, contributed a higher proportion of studies directly aligned with biomedical applications, particularly in wound healing and drug delivery systems. ScienceDirect, on the other hand, provided a consistent set of

studies focused on material reinforcement and composite behavior, reinforcing its relevance for the engineering axis of the review.

The filtering process also played a decisive role in shaping the final corpus. The restriction to peer-reviewed articles and full-text availability ensured methodological reliability, while the focus on English-language publications facilitated standardization in data extraction and interpretation. At the same time, these criteria may have excluded regionally relevant studies published in other languages, which reflects a broader structural limitation in global scientific indexing.

Taken together, the data presented in Table 1 reveal not only the methodological rigor of the search process but also the epistemological dispersion of the field. The uneven distribution of studies across domains underscores the necessity of an integrative approach capable of bridging molecular characterization, biomedical innovation, and engineering applications. This observation directly supports the rationale of the present review, which seeks to reorganize dispersed evidence into a coherent analytical framework grounded in the multifunctionality of nanocellulose.

## **Inclusion and Exclusion Criteria**

Eligibility criteria were established before the screening stage in order to ensure transparency, reproducibility, and analytical coherence. These criteria were directly aligned with the objective of the review and with the guiding research question.

Inclusion criteria:

- Original articles and review studies published in peer-reviewed journals.
- Studies addressing nanocellulose, cellulose nanocrystals, or cellulose nanofibers derived from lignocellulosic biomass, with special relevance to xerophytic or agriculturally significant plant sources.
- Studies examining physicochemical, structural, mechanical, thermal, or biological

properties of nanocellulose.

- Studies reporting applications related to controlled drug delivery, wound dressings, biotextiles, tissue-related biomedical uses, green composites, or sustainable construction materials.
- Studies with sufficient methodological and analytical detail to permit extraction of relevant variables for synthesis.
- Publications written in English and directly accessible in full text.

Exclusion criteria:

- Editorials, conference abstracts, dissertations, theses, book chapters, patents, technical notes, and non-peer-reviewed documents.
- Studies focused on cellulose at the macro or micro scale without specific treatment of nanocellulose.
- Publications unrelated to the biomedical or engineering applicability defined in the scope of the review.
- Studies centered on unrelated nanomaterials without direct comparison or integration with nanocellulose.
- Papers lacking sufficient methodological description, outcome clarity, or direct relevance to the research question.
- Duplicate records identified across databases.

The screening process was conducted in successive stages. First, titles and abstracts were read to eliminate clearly irrelevant studies. Second, the remaining publications were analyzed in full text to verify alignment with the review objective, adequacy of methodological description, and substantive contribution to at least one of the three analytical axes of the study.

This staged procedure reduced noise in the sample and ensured that the final body of evidence

would be both conceptually focused and methodologically defensible. Because the topic intersects multiple fields, particular care was taken not to exclude studies solely on the basis of disciplinary language, provided that they offered relevant data on nanocellulose properties or applications.

### **Data Extraction and Analytical Strategy**

After the eligibility process, the selected studies were subjected to systematic data extraction using an analytical matrix developed specifically for this review. The extraction instrument was structured to capture bibliographic, methodological, and thematic information, allowing the organization of evidence into comparable categories.

The following variables were prioritized: authorship, year of publication, biomass source, nanocellulose type, extraction or processing method, physicochemical properties reported, mechanical or thermal performance, biological outcomes when applicable, application field, and principal conclusions. This procedure ensured uniformity in the reading of studies and supported the later synthesis of convergent and divergent findings.

The analytical strategy adopted a thematic categorization model compatible with the integrative review method, enabling the articulation of studies with different designs under a common interpretive logic (Mendes; Silveira; Galvão, 2008; Souza; Silva; Carvalho, 2010). Rather than merely describing isolated results, the review sought to identify recurring explanatory patterns linking biomass origin, nanoscale structure, and technological performance. To that end, the extracted data were organized into three major interpretive axes:

- Molecular and structural properties, including crystallinity, aspect ratio, morphology, surface chemistry, tensile behavior, and other parameters relevant to nanoscale performance.
- Biomedical applications, including wound dressings, hydrogel systems, drug delivery platforms, cytocompatibility, and tissue repair potential.

- Engineering applications, including polymer reinforcement, composite development, matrix interaction, crack mitigation, and sustainable construction uses.

This categorization was not treated as a rigid compartmentalization, but as an analytical device for understanding how the intrinsic properties of nanocellulose condition its multifunctional behavior across sectors. Thus, evidence was interpreted comparatively, with attention to the transferability of structural advantages from one application field to another. For instance, high water retention and network formation were examined not only in relation to wound healing systems, but also in connection with matrix behavior in composite materials. Similarly, crystallinity and aspect ratio were analyzed both as determinants of mechanical reinforcement and as variables with possible biological implications.

A critical synthesis was then developed from the thematic matrix, emphasizing three dimensions: consistency of evidence, unresolved contradictions, and research gaps. This interpretive stage was essential because the objective of an integrative review extends beyond descriptive compilation.

In line with the methodological premises adopted here, the synthesis aimed to produce a theoretically informed and application-oriented reading of the literature, capable of supporting the proposition of a broader conceptual model centered on xerophytic biomass valorization. Therefore, the methodology combined systematic retrieval, explicit eligibility criteria, structured extraction, and interpretive integration, producing a robust basis for the discussion of nanocellulose as a multifunctional platform for health technologies and sustainable material systems.

## **XEROPHYTIC NANOCELLULOSE: STRUCTURE AND PROPERTIES**

### **Extraction and Synthesis from Agricultural and Xerophytic Biomass**

The extraction of nanocellulose from lignocellulosic biomass relies on a sequence of

physicochemical processes designed to isolate crystalline domains while removing amorphous fractions such as hemicellulose and lignin. Among these methods, acid hydrolysis remains the most widely employed technique for producing cellulose nanocrystals, whereas mechanical fibrillation processes, including high-shear homogenization and ultrasonication, are predominantly used to obtain cellulose nanofibers (Chaka, 2022; Ghazy et al., 2016).

Acid hydrolysis, typically performed using sulfuric or hydrochloric acid, selectively degrades amorphous cellulose regions, yielding nanocrystals with high crystallinity indices. Chaka (2022, p. 586) emphasizes that “acid hydrolysis removes disordered regions, leaving rod-like crystalline nanoparticles,” a structural transformation that underpins the mechanical performance of nanocellulose. However, this process is not without limitations, as excessive hydrolysis can reduce particle size heterogeneity and compromise yield efficiency.

Mechanical fibrillation, in contrast, preserves both crystalline and amorphous domains, generating long and flexible nanofibers with high aspect ratios. The effectiveness of this method is strongly influenced by pre-treatment strategies such as alkaline delignification and bleaching. Widyawati et al. (2025, p. 213) report that “acid hydrolysis following decortication enhances cellulose purity and facilitates nanofiber formation,” highlighting the importance of combined treatments for optimizing nanostructure isolation.

Studies involving agro-industrial residues reinforce the viability of these approaches. Ghazy et al. (2016) demonstrated that sugarcane bagasse can yield nanocellulose with crystallinity indices exceeding 70%, while Gallardo-Sánchez et al. (2019) reported efficient cellulose pulp extraction from agave bagasse, emphasizing its potential as a precursor for nanoscale materials. Pirah et al. (2022) further showed that lignocellulosic extraction from sisal fibers enables the production of stable emulsions, indicating that nanocellulose functionality extends beyond structural reinforcement to interfacial applications.

Despite these advances, extraction processes remain energy-intensive and often lack standardization, particularly when applied to xerophytic biomass. This raises a critical question: to

what extent do conventional extraction protocols adequately capture the intrinsic structural advantages of plants adapted to extreme environments?

### **Structural Properties: Crystallinity and Aspect Ratio**

The functional performance of nanocellulose is fundamentally governed by its crystallinity and aspect ratio, two parameters that define its mechanical behavior, surface reactivity, and biological interactions. High crystallinity is associated with increased stiffness and thermal stability, whereas elevated aspect ratios enhance stress transfer efficiency within composite matrices (Wang et al., 2019; Mariano et al., 2016).

Mariano et al. (2016, p. 2286) observed that “the aspect ratio of cellulose nanocrystals plays a critical role in reinforcement efficiency,” particularly in polymer matrices, where load distribution depends on fiber geometry. This relationship becomes even more pronounced at the nanoscale, where minor variations in length-to-diameter ratio can significantly alter macroscopic material properties.

From a biological perspective, crystallinity also influences cellular responses. Wang et al. (2019) demonstrated that nanocellulose with higher crystallinity indices exhibits distinct interactions with biological systems, affecting protein adsorption and cellular adhesion. This finding introduces a critical dimension to the discussion, as structural optimization for mechanical performance may not always align with optimal biocompatibility.

Experimental data from sisal-derived nanocellulose reinforce these observations. Yudhanto et al. (2024) reported crystallinity indices ranging from 65% to 78%, depending on extraction conditions, with corresponding improvements in thermal stability and tensile strength. These results suggest that process parameters directly influence structural outcomes, yet they also reveal a lack of consensus regarding optimal crystallinity thresholds for multifunctional applications.

Such variability exposes a broader epistemological tension within the field. While high crystallinity and aspect ratio are often treated as universally desirable attributes, their effects are

context-dependent, raising the need for a more nuanced understanding of structure–function relationships in nanocellulose systems.

### **Nanocellulose from Cactaceae and Agave Species**

The exploration of nanocellulose derived from xerophytic species, particularly those belonging to the Cactaceae and Agave genera, has revealed promising structural and functional characteristics. These plants, shaped by extreme environmental conditions, exhibit fibrous architectures that are intrinsically optimized for mechanical resistance and water retention.

Orrabalis et al. (2019) characterized nanocellulose extracted from *Cereus forbesii*, reporting well-defined nanofibrillar structures with high crystallinity and uniform morphology. Similarly, Rosli et al. (2013, p. 1898) identified that nanocrystals derived from *Agave angustifolia* exhibit “high crystallinity and rod-like morphology,” reinforcing their suitability for reinforcement applications.

Further investigations into agave-derived nanofibers corroborate these findings. Krishnadev et al. (2020; 2021) demonstrated that nanofibrillated cellulose obtained from *Agave americana* displays significant improvements in mechanical performance when incorporated into polymer matrices. Sumarago et al. (2024) extended this analysis by reporting consistent nanofiber production from maguey fibers, with properties comparable to those obtained from more extensively studied lignocellulosic sources.

Biocompatibility studies also contribute to this body of evidence. Evdokimova et al. (2021, p. 455) noted that nanofibers derived from *Agave americana* are “cytocompatible and suitable for biomedical applications,” suggesting that xerophytic biomass can simultaneously meet structural and biological performance requirements.

Despite these advances, the literature remains disproportionately focused on a limited number of species, often neglecting the diversity of xerophytic flora present in ecosystems such as the Caatinga. This selective attention raises concerns regarding the generalizability of current findings

and highlights the need for broader exploration of underrepresented species such as *Cereus jamacaru*.

### **Influence of Environmental Stress (Caatinga Conditions)**

The structural properties of nanocellulose derived from xerophytic plants cannot be fully understood without considering the environmental conditions that shape plant development. Water scarcity, high solar radiation, and nutrient limitations impose selective pressures that influence cell wall composition, fiber density, and molecular organization.

Gupta and Shukla (2020) argue that lignocellulosic biomass derived from stress-adapted plants often exhibits enhanced structural integrity, a feature that can be directly translated into improved nanomaterial performance. Mateo et al. (2021) further emphasize that agricultural and environmental conditions significantly affect cellulose morphology, reinforcing the idea that biomass origin is not a neutral variable in nanocellulose production.

In the context of the Caatinga, prolonged drought conditions may induce higher degrees of cellulose crystallinity and fiber compactness as adaptive responses to water deficit. This hypothesis, although still underexplored experimentally, provides a compelling framework for understanding xerophytic plants as natural nanofactories. Rather than viewing environmental stress as a limitation, it can be interpreted as a driver of structural optimization at the molecular level (Gupta; Shukla, 2020; Mateo et al., 2021).

This perspective challenges conventional approaches to biomaterial sourcing, which often prioritize yield and availability over structural quality. By shifting the focus toward environmentally conditioned biomass, it becomes possible to reconceptualize plant stress as a source of innovation. Such a shift raises an essential question for future research: are current nanocellulose production paradigms overlooking the intrinsic advantages encoded in extreme ecosystems? Evidence suggests that lignocellulosic biomass properties are strongly influenced by environmental and physiological factors, reinforcing the importance of ecological context in nanocellulose performance (Gupta;

Shukla, 2020).

Taken together, the evidence presented in this section supports the notion that xerophytic plants represent a strategically valuable yet underutilized source of nanocellulose. Their molecular architecture, shaped by environmental adversity, offers a foundation for the development of high-performance materials with applications that extend from biomedical systems to sustainable construction (Mateo et al., 2021; Gandhi et al., 2024).

## **HEALTH APPLICATIONS: SMART DRESSINGS AND DELIVERY**

### **Nanocellulose as Hydrogel Matrix**

The emergence of nanocellulose as a hydrogel-forming material has redefined the design of advanced wound dressings, particularly due to its intrinsic hydrophilicity and capacity for moisture retention. These properties are not merely advantageous but functionally decisive in maintaining an optimal wound microenvironment, which is critical for tissue regeneration and infection control. Hydrogels based on nanocellulose exhibit high water absorption capacity, structural stability, and permeability to gases, enabling a balance between hydration and oxygen exchange (Bačáková et al., 2019; Bačáková et al., 2018).

From a physicochemical perspective, the dense network of hydroxyl groups on nanocellulose surfaces promotes hydrogen bonding with water molecules, resulting in swelling behavior that can exceed several times the material's dry weight. Anisa et al. (2021, p. 60) highlight that “nanocellulose-based hydrogels demonstrate excellent water retention and structural integrity,” reinforcing their applicability in wound care systems where dehydration can delay healing processes.

However, the same hydrophilic nature that enhances performance also introduces challenges related to mechanical stability and degradation control. Excessive swelling may compromise structural integrity under mechanical stress, particularly in dynamic biological environments. This duality raises a fundamental question: how can nanocellulose hydrogels be engineered to balance hydration

capacity with mechanical resilience without compromising biocompatibility?

### **Antibacterial and Bioactive Functionalization**

The functionalization of nanocellulose with bioactive compounds has emerged as a central strategy to enhance its therapeutic performance. In its native form, nanocellulose lacks intrinsic antimicrobial activity, which necessitates the incorporation of active agents capable of inhibiting microbial proliferation and modulating inflammatory responses.

Curcumin-loaded nanocellulose scaffolds exemplify this approach. Alavi et al. (2022, p. 11) report that “curcumin incorporated into cellulose-based scaffolds exhibits significant antibacterial and wound healing activity,” demonstrating the synergistic effect between the carrier matrix and the bioactive compound. Similarly, Firmanda et al. (2022) explored the incorporation of natural extracts from coffee and tea into cellulose composites, showing enhanced antimicrobial properties and suggesting the feasibility of integrating plant-derived compounds into nanocellulose matrices.

Recent advances have also considered the integration of nanoparticles and hybrid systems. Rodrigues et al. (2025) emphasize that advanced dressings incorporating organic and carbon-based nanoparticles can significantly improve regenerative outcomes, particularly by enhancing antimicrobial efficiency and cellular proliferation. These findings indicate that nanocellulose functions not merely as a passive scaffold but as an active delivery platform capable of hosting multifunctional agents.

Despite these advances, the selection of bioactive compounds remains largely empirical, often driven by availability rather than mechanistic compatibility with the nanocellulose matrix. This reveals a critical gap in the rational design of functionalized systems, where interactions between carrier and active agent are not fully understood at the molecular level.

### **Controlled Drug Release Mechanisms**

The ability of nanocellulose to act as a controlled drug delivery platform is closely associated with its porous structure, surface chemistry, and capacity for chemical modification. Drug release from nanocellulose-based systems is typically governed by diffusion, swelling, and degradation mechanisms, which can be modulated through structural and chemical tuning (Patil et al., 2021).

Stimuli-responsive systems have attracted particular attention, especially those sensitive to pH and temperature variations. These systems are designed to release therapeutic agents in response to changes in the wound environment, such as infection-induced acidity or localized inflammation. Joseph et al. (2020, p. 229) note that “nanocellulose composites can be engineered to provide controlled and sustained drug release,” highlighting their potential for reducing dosing frequency and improving therapeutic efficiency.

Quantitative studies indicate that nanocellulose-based systems can sustain drug release over extended periods, ranging from several hours to days, depending on matrix composition and crosslinking density. This temporal control is essential in chronic wound management, where prolonged exposure to therapeutic agents is required.

Nevertheless, the predictability of release kinetics remains a challenge. Variations in nanocellulose morphology, degree of functionalization, and environmental conditions can lead to significant deviations in release profiles. This variability underscores the need for standardized design protocols capable of ensuring reproducibility across different applications.

## **Tissue Engineering and Wound Healing Performance**

The application of nanocellulose in tissue engineering and wound healing is supported by its cytocompatibility, low toxicity, and ability to mimic extracellular matrix structures. These characteristics facilitate cell adhesion, proliferation, and differentiation, which are essential processes in tissue regeneration.

Koshy et al. (2024, p. 18330) demonstrated that nanocellulose-based films promote “enhanced

cell viability and accelerated wound closure,” indicating their effectiveness as regenerative materials. Similarly, Jiang et al. (2021) reported that composite dressings combining alginate and nanofibrillated cellulose exhibit improved mechanical stability and biological performance, reinforcing the benefits of hybrid systems.

Emerging research has also explored alternative biomass sources for biomedical nanocellulose. Umaphathi et al. (2025) investigated nanocellulose derived from banana stem fibers, highlighting its biomedical potential and reinforcing the broader applicability of lignocellulosic materials in tissue engineering contexts. Although not derived from xerophytic species, these findings contribute to the understanding of how plant-based nanocellulose can be adapted for regenerative applications.

Despite consistent evidence of cytocompatibility, questions remain regarding long-term interactions between nanocellulose and biological systems. Issues related to biodegradability, immune response, and long-term stability are not yet fully resolved, particularly in complex clinical scenarios. These uncertainties suggest that, while nanocellulose-based dressings represent a significant advancement, their transition from experimental systems to standardized clinical solutions requires further investigation.

Table 2 systematizes the principal biomedical applications of nanocellulose-based systems, organizing evidence according to material type, functionalization strategy, application domain, and observed outcomes. This structured synthesis highlights the versatility of nanocellulose as a multifunctional platform capable of integrating physicochemical properties with biological performance. The diversity of configurations presented reflects not only the adaptability of nanocellulose but also the absence of a standardized design paradigm across studies.

The table reveals a clear trend toward hybridization strategies, in which nanocellulose is combined with polymers, bioactive compounds, or nanoparticles to enhance its functional profile. Such combinations expand the applicability of the material beyond passive scaffolding, positioning it as an active component in therapeutic systems. The inclusion of both cellulose nanocrystals and nanofibers further illustrates how structural variations influence application-specific performance.

Table 2. Biomedical Applications of Nanocellulose-Based Systems

Type of Nanocellulose	Functionalization Strategy	Application	Key Outcomes
CNF (Nanofibers)	Pure hydrogel matrix	Wound dressing	High moisture retention; structural stability; enhanced healing environment
CNC (Nanocrystals)	Curcumin incorporation	Antibacterial dressing	Significant antimicrobial activity; accelerated wound healing
CNF + Alginate	Ionic crosslinking	Skin regeneration	Improved mechanical strength; enhanced cell adhesion and proliferation
CNF-based composites	Plant-derived bioactives (coffee, tea extracts)	Bioactive wound dressing	Antioxidant and antibacterial effects; improved tissue response
CNF/CNC hybrid systems	Nanoparticle incorporation (organic/carbon-based)	Advanced regenerative dressings	Increased antimicrobial efficiency; improved regeneration kinetics
Nanocellulose matrices	Drug loading (diffusion-controlled systems)	Drug delivery	Sustained release over time; reduced dosing frequency
Nanocellulose films	Surface modification and polymer blending	Tissue engineering scaffolds	High cytocompatibility; enhanced cell viability and tissue regeneration

Source: Developed by the authors.

A critical examination of the data presented in Table 2 reveals that the biomedical performance of nanocellulose is strongly dependent on its functionalization strategy rather than solely on its intrinsic properties. While native nanocellulose demonstrates favorable characteristics such as hydrophilicity and cytocompatibility, its transformation into an effective biomedical material typically requires the incorporation of additional functional elements. This observation aligns with findings by Bačáková et al. (2019), who emphasize the need for material modification to achieve optimal biological performance.

The predominance of wound healing applications underscores the compatibility between nanocellulose hydrogels and the physiological requirements of tissue repair. High moisture retention,

structural integrity, and permeability are recurrent outcomes across studies (Anisa et al., 2021). However, the table also exposes a reliance on empirical approaches to functionalization, particularly in the selection of bioactive compounds. For instance, the incorporation of curcumin and plant extracts, although effective, is often guided by known biological activity rather than by a systematic understanding of interactions with the nanocellulose matrix (Alavi et al., 2022; Firmanda et al., 2022).

The emergence of nanoparticle-enhanced systems introduces an additional layer of complexity. While these systems demonstrate improved antimicrobial and regenerative performance (Rodrigues et al., 2025), they also raise concerns regarding long-term biocompatibility and potential cytotoxicity. This tension between enhanced functionality and biological safety reflects a broader challenge in the field of advanced biomaterials.

Another critical insight concerns drug delivery systems. Although sustained release profiles are consistently reported, the variability in release kinetics across studies suggests a lack of standardization in matrix design (Patil et al., 2021; Joseph et al., 2020). This variability may limit the translation of experimental systems into clinical applications, where reproducibility is essential.

The data indicate that nanocellulose-based systems are approaching a threshold of technological maturity, yet remain constrained by unresolved questions regarding long-term stability, degradation behavior, and scalability. The absence of convergence toward standardized formulations suggests that the field is still in a phase of exploratory diversification rather than consolidation.

Taken together, Table 2 reinforces the notion that nanocellulose is not a finished material, but a platform technology whose performance depends on deliberate and context-specific design choices. This reinforces the need for integrative frameworks capable of linking molecular properties, functionalization strategies, and application outcomes in a coherent and predictive manner.

Collectively, the findings discussed in this section reveal that nanocellulose occupies a strategic position at the intersection of material science and biomedical innovation. Its capacity to function as a hydrogel matrix, a carrier of bioactive compounds, and a controlled drug delivery system underscores its multifunctionality. At the same time, the limitations identified across studies

highlight the need for a more integrated and mechanistically grounded approach to the design of smart biomaterials.

## **ENGINEERING APPLICATIONS: GREEN NANOCELLULOSE COMPOSITES**

### **Reinforcement Mechanisms in Polymer and Cement Matrices**

The incorporation of nanocellulose into polymeric and cementitious matrices has been widely recognized as a strategy to enhance mechanical performance through nanoscale reinforcement mechanisms. At the core of this behavior lies the efficient transfer of stress between the matrix and the nanofibers, a process strongly influenced by interfacial adhesion and fiber dispersion. Nanocellulose, due to its high aspect ratio and surface reactivity, promotes effective load transfer, thereby increasing tensile strength and stiffness of composite materials (De Vilhena et al., 2024; Yudhanto et al., 2021).

Experimental evidence indicates that even low concentrations of nanocellulose can significantly alter the mechanical response of composite systems. De Vilhena et al. (2024) demonstrated that the incorporation of sisal nanofibers into starch-based films resulted in measurable improvements in tensile properties, suggesting strong interfacial interactions. Similarly, Yudhanto et al. (2021, p. 991) reported that “nanofiber reinforcement enhances tensile strength and mechanical stability,” highlighting the role of nanoscale fibers in distributing applied stress more uniformly.

In cementitious matrices, the reinforcement effect is further complemented by crack-bridging mechanisms. Nanocellulose fibers can span microcracks, delaying their propagation and increasing fracture resistance. Rendón et al. (2019, p. 9815) observed that cellulose nanofibers “improve mechanical properties and structural integrity of composites,” indicating that their presence contributes not only to strength but also to durability. These findings suggest that nanocellulose operates simultaneously at multiple scales, influencing both microstructural cohesion and macroscopic performance.

Despite these promising results, challenges related to homogeneous dispersion and fiber agglomeration persist. Poor dispersion can lead to stress concentration points, undermining the

reinforcing effect and potentially reducing mechanical performance. This limitation raises a critical issue: how can processing techniques be optimized to ensure uniform nanocellulose distribution in large-scale construction materials?

### **Nanopore Filling and Durability Enhancement**

Beyond reinforcement, nanocellulose contributes to the modification of matrix porosity, acting as a filler of nanoscale voids and thereby improving material compactness. This nanopore filling effect is particularly relevant in cement-based systems, where porosity directly influences permeability, durability, and susceptibility to environmental degradation.

Amanda et al. (2022) demonstrated that the incorporation of sisal nanofibers into resin-based systems enhances bonding strength, suggesting improved interfacial cohesion at the microstructural level. Although conducted in a dental context, these findings are transferable to construction materials, where similar mechanisms govern adhesion and mechanical performance. Pirah et al. (2022, p. 8) further emphasize that lignocellulosic fibers “improve emulsion stability and structural integrity,” indicating that nanocellulose contributes to the homogenization of composite systems.

The reduction of microcracks is another critical outcome associated with nanocellulose incorporation. By occupying nanoscale voids and reinforcing weak zones, nanocellulose limits crack initiation and propagation. This effect translates into increased tensile strength and improved resistance to mechanical fatigue. Quantitative studies suggest that nanocellulose can reduce porosity and enhance tensile performance by measurable margins, although the magnitude of these improvements varies depending on matrix composition and processing conditions.

Nevertheless, the durability benefits of nanocellulose are not universally consistent. Variations in fiber treatment, moisture sensitivity, and long-term degradation behavior can influence performance over time. These inconsistencies highlight the need for standardized protocols capable of ensuring reproducible outcomes across different material systems.

## **Sisal and Agave Nanofibers in Green Composites**

Sisal and agave-derived nanofibers have attracted increasing attention as reinforcement agents in green composites, particularly due to their abundance, renewability, and favorable mechanical properties. These fibers, when processed at the nanoscale, exhibit enhanced surface area and improved interaction with polymer matrices, resulting in composites with superior mechanical and thermal performance.

Krishnadev et al. (2021, p. 8132) reported that nanofibrillated cellulose from *Agave americana* “improves tensile properties and thermal stability of polymer composites,” demonstrating its effectiveness as a reinforcing agent. Similarly, Sumarago et al. (2024) showed that nanocellulose derived from maguey fibers exhibits consistent structural characteristics, supporting its application in composite systems.

The performance of these materials is closely linked to their morphological and structural attributes. High aspect ratios facilitate stress transfer, while crystallinity contributes to stiffness and thermal resistance. These characteristics position sisal and agave nanofibers as competitive alternatives to synthetic reinforcements, particularly in applications where sustainability and environmental impact are critical considerations.

However, the adoption of these materials in large-scale construction remains limited. Issues related to scalability, cost efficiency, and compatibility with existing industrial processes continue to constrain their implementation. This gap between laboratory performance and industrial application underscores a broader challenge in translating bio-based innovations into practical solutions.

## **Carbon Sequestration and Environmental Impact**

The integration of nanocellulose into construction materials extends beyond mechanical

performance, encompassing broader environmental implications. As a bio-based material derived from lignocellulosic biomass, nanocellulose inherently contributes to carbon sequestration by storing atmospheric carbon within structural applications.

Gupta and Shukla (2020) highlight that lignocellulosic materials represent a sustainable alternative to synthetic polymers, not only due to their renewability but also because of their capacity to reduce carbon emissions. Gandhi et al. (2024) further emphasize that transforming agricultural waste into nanocellulose adds value to biomass while mitigating environmental impact, reinforcing the role of these materials in circular economy models.

From a lifecycle perspective, the use of nanocellulose in construction materials can reduce the carbon footprint associated with conventional building practices. By partially replacing cement or synthetic polymers, nanocellulose-based composites contribute to lower greenhouse gas emissions and improved sustainability metrics. At the same time, the biodegradability of these materials offers an advantage in end-of-life scenarios, reducing environmental persistence.

Despite these benefits, the environmental performance of nanocellulose-based systems is not unequivocally positive. Energy-intensive extraction processes and chemical treatments may offset some of the sustainability gains, particularly when not optimized for efficiency. This paradox underscores the importance of developing integrated production models, such as closed-loop biorefineries, capable of maximizing resource efficiency while minimizing environmental impact.

In this context, nanocellulose should not be viewed solely as a material innovation, but as part of a broader systemic transformation in how construction materials are sourced, produced, and utilized. The challenge lies in aligning technological performance with environmental responsibility, ensuring that advances in material science translate into genuinely sustainable solutions.

## **XEROPHYTIC BIOREFINERY: A CLOSED-LOOP MODEL**

### **Theoretical Foundation of the Concept**

The increasing demand for sustainable materials has exposed the limitations of linear production models, particularly those dependent on extractive and waste-generating processes. In contrast, the integration of nanotechnology with circular economy principles offers a pathway toward regenerative material systems, in which resource efficiency and environmental feedback are structurally embedded. Within this paradigm, nanocellulose emerges not only as a high-performance material but also as a vector for rethinking production logics in resource-constrained environments.

The concept of a xerophytic closed-loop biorefinery is grounded in the convergence of three domains: lignocellulosic valorization, nanoscale engineering, and ecological regeneration. Lignocellulosic biomass has already been recognized as a renewable feedstock capable of generating high-value nanomaterials (Gupta; Shukla, 2020; Gandhi et al., 2024). However, conventional approaches tend to isolate production from ecological context, neglecting the potential for reintegration of byproducts into local environmental systems.

Nanocellulose technologies, due to their versatility, allow the transformation of low-value biomass into advanced materials with biomedical and structural applications (Patil et al., 2021; Joseph et al., 2020). As noted by Gupta and Shukla (2020), lignocellulosic biomass represents “a sustainable source for advanced functional materials,” yet the broader systemic implications of this transformation remain underexplored. The proposed model challenges this limitation by embedding nanocellulose production within a circular and territorially grounded framework.

### **System Model: From Biomass to High-Tech Materials**

The xerophytic closed-loop biorefinery can be conceptualized as an integrated system in which biomass inputs, transformation processes, and high-value outputs are dynamically interconnected. The primary input consists of xerophytic plant biomass, particularly species such as *Cereus jamacaru* and *Agave sisalana*, whose structural adaptations provide an advantageous starting point for nanocellulose extraction.

Through sequential processing stages including pretreatment, hydrolysis, and fibrillation, this biomass is converted into nanocellulose with tailored physicochemical properties. Studies on agave and related species demonstrate that such processes can yield nanofibers with high crystallinity and mechanical performance (Krishnadev et al., 2020; Sumarago et al., 2024). These materials can then be directed toward multiple application streams, including biomedical systems and structural composites, illustrating the multifunctional nature of nanocellulose platforms.

Rendón et al. (2019, p. 9810) highlight that nanocellulose-based composites “can be tailored for diverse industrial applications,” reinforcing the feasibility of a multi-output production system. Similarly, Koshy et al. (2024) demonstrate that nanocellulose films can be engineered for biomedical use, while Yudhanto et al. (2021) emphasize their role in enhancing mechanical performance in composite materials. These convergent findings support the notion that a single biomass input can generate a spectrum of high-value outputs.

Nevertheless, the transition from linear to integrated systems raises important questions regarding process optimization and resource allocation. Can a single production chain effectively meet the distinct requirements of biomedical and construction applications without compromising quality or efficiency?

### **Byproduct Reintegration and Soil Regeneration**

A defining feature of the xerophytic closed-loop biorefinery lies in the reintegration of processing byproducts into the ecological system from which the biomass is derived. Unlike conventional industrial models, where residues are treated as waste, this framework treats them as functional inputs for environmental regeneration.

During nanocellulose extraction, significant quantities of residual biomass, including lignin fractions and mucilaginous compounds, are generated. These materials possess hydrophilic and structural properties that can be repurposed as soil conditioners, particularly in semi-arid environments

where water retention is a critical limiting factor. Pirah et al. (2022) demonstrate that lignocellulosic residues can stabilize emulsions and enhance structural cohesion, properties that are transferable to soil systems in the form of moisture-retaining agents.

This reintegration process aligns with observations by Mateo et al. (2021), who emphasize that agricultural residues can be transformed into value-added products, thereby reducing environmental impact. In parallel, Chaka (2022) notes that the utilization of biomass residues contributes to resource efficiency and waste minimization. Such findings support the viability of a feedback loop in which material outputs are partially redirected to sustain the ecological base of production.

The implications of this approach extend beyond material efficiency. By enhancing soil structure and water retention, the reintegration of byproducts contributes to the resilience of xerophytic ecosystems, potentially mitigating the effects of drought and land degradation. This raises a critical consideration: can material production systems be designed not only to minimize harm but to actively restore ecological function?

## **Socio-Environmental and Technological Implications**

The implementation of a xerophytic closed-loop biorefinery carries significant socio-environmental implications, particularly in semi-arid regions such as the Caatinga. These territories are often characterized by resource scarcity, economic vulnerability, and limited access to advanced technologies. Within this context, the valorization of local biomass into high-value nanomaterials represents a potential pathway for technological inclusion and regional development.

From an environmental perspective, the integration of bio-based materials into industrial systems contributes to carbon sequestration and reduced reliance on fossil resources (Gupta; Shukla, 2020; Gandhi et al., 2024). At the same time, the localized nature of biomass sourcing reduces transportation-related emissions and supports decentralized production models. This alignment between environmental sustainability and territorial specificity suggests that xerophytic biorefineries

could function as nodes of distributed innovation.

The technological dimension of this model is equally significant. By linking nanotechnology with locally available resources, it becomes possible to reconfigure the geography of innovation, shifting it from centralized industrial hubs to peripheral regions. However, this transformation is not without challenges. Issues related to technical expertise, infrastructure, and scalability remain substantial barriers to implementation.

Evdokimova et al. (2021, p. 458) emphasize that nanocellulose production “requires controlled processing conditions to ensure reproducibility,” underscoring the need for technical standardization. Similarly, De Vilhena et al. (2024) highlight the importance of optimizing material formulations to achieve consistent performance. These requirements suggest that the success of xerophytic biorefineries will depend not only on material availability but also on the development of robust technological frameworks.

From a critical perspective, the concept also intersects with debates on environmental justice. The transformation of semi-arid regions into sources of advanced materials raises questions about resource governance, benefit distribution, and local participation. Will these innovations empower local communities, or will they reproduce existing patterns of extraction under a new technological paradigm?

Table 3 presents a conceptual and operational synthesis of the xerophytic closed-loop biorefinery model, integrating material production, technological transformation, and ecological feedback into a unified system. The structure of the table reflects a process-oriented perspective, in which each stage is defined not only by its inputs and outputs but also by its contribution to environmental regeneration. This configuration departs from conventional linear production chains by explicitly incorporating feedback loops that reconnect industrial processes to ecological functions.

The model is organized into five interconnected components: biomass production, pretreatment, nanocellulose extraction, material application, and byproduct reutilization. Each component represents a functional stage within the system, yet none operates in isolation. Instead, the

outputs of one stage become inputs or feedback elements for others, forming a dynamic cycle. This structure aligns with circular economy principles while embedding them within the specific context of xerophytic ecosystems.

Table 3. Integrated Model of Xerophytic Closed-Loop Biorefinery

System Component	Inputs	Processes	Outputs	Environmental Feedback Loops
Biomass Production	Xerophytic plants ( <i>Cereus jamacaru</i> , <i>Agave sisalana</i> )	Cultivation under semi-arid conditions; harvesting	Lignocellulosic biomass	Adapted growth; low water demand; resilience to drought
Pretreatment Stage	Raw biomass	Mechanical processing; alkaline treatment; delignification	Purified cellulose pulp	Residual lignin and organic fractions redirected for reuse
Nanocellulose Extraction	Cellulose pulp	Acid hydrolysis; mechanical fibrillation	CNC and CNF with high crystallinity and aspect ratio	Process optimization to reduce chemical waste and energy consumption
Material Application	Nanocellulose	Functionalization; composite formation; hydrogel synthesis	Biomedical devices; green composites; smart materials	Carbon storage in materials; reduction of synthetic material demand
Byproduct Reutilization	Residual biomass; mucilage; lignin fractions	Conversion into soil conditioners; moisture-retaining agents	Soil enrichment; hydric conditioning	Improved soil structure; increased water retention; ecosystem resilience

Source: Developed by the authors.

A critical analysis of Table 3 reveals that the xerophytic closed-loop biorefinery is not merely a technical workflow but a systemic reconfiguration of material production. The most significant innovation lies in the integration of environmental feedback loops, which transform what would traditionally be considered waste into functional inputs for ecological regeneration. This shift challenges the dominant paradigm of resource extraction and disposal, proposing instead a model of continuous material and environmental exchange.

The role of xerophytic biomass as the primary input is particularly strategic. Plants such as *Cereus jamacaru* and *Agave sisalana* are naturally adapted to water-scarce environments, requiring minimal external inputs while producing structurally robust fibers. This intrinsic efficiency reduces the environmental cost of raw material production and enhances the sustainability of the entire system (Mateo et al., 2021; Gupta; Shukla, 2020). Furthermore, the transformation of this biomass into nanocellulose leverages its naturally optimized structure, as previously discussed in relation to crystallinity and mechanical performance.

The extraction stage, however, represents a critical bottleneck. While acid hydrolysis and mechanical fibrillation are effective in producing high-quality nanocellulose, they are also associated with chemical consumption and energy demand (Chaka, 2022; Ghazy et al., 2016). This tension highlights the importance of process optimization within the biorefinery model. Without improvements in efficiency, the environmental benefits of bio-based materials may be partially offset by the impacts of their production.

The application stage demonstrates the multifunctionality of nanocellulose, which can be directed toward biomedical systems, composite materials, and smart technologies. This versatility is central to the economic viability of the model, as it enables diversification of outputs and value streams (Rendón et al., 2019; Patil et al., 2021). At the same time, it raises questions about process standardization, since different applications require distinct material properties and processing conditions.

Perhaps the most transformative aspect of the model lies in the reintegration of byproducts. The conversion of residual biomass and mucilage into soil conditioners introduces a regenerative dimension that extends beyond material efficiency. By improving soil structure and water retention, these byproducts contribute to the resilience of semi-arid ecosystems, effectively closing the loop between production and environmental sustainability (Pirah et al., 2022; Mateo et al., 2021). This approach reframes waste as a resource, aligning technological processes with ecological cycles.

Nevertheless, the implementation of such a system is contingent upon overcoming

several structural challenges. Technical complexity, infrastructure requirements, and the need for interdisciplinary coordination may limit scalability, particularly in regions with limited access to advanced technologies. Moreover, the distribution of benefits within this system remains an open question, especially in socioeconomically vulnerable contexts.

Taken together, the xerophytic closed-loop biorefinery represents more than a technological proposal; it constitutes a conceptual reconfiguration of how materials, environments, and societies interact. By integrating nanocellulose production with ecological regeneration and territorial development, this model challenges the boundaries between material science and socio-environmental systems. Its viability, however, will depend on the capacity to align scientific innovation with contextual realities, ensuring that technological advances translate into sustainable and equitable outcomes.

## **INTEGRATIVE DISCUSSION**

### **Cross-Axis Synthesis (Molecular → Health → Engineering)**

The evidence synthesized across molecular, biomedical, and engineering domains reveals that nanocellulose operates as a truly trans-scalar material, whose properties are not confined to a single application field but rather propagate across functional systems. Crystallinity and aspect ratio, initially discussed as structural parameters, emerge as central determinants not only of mechanical reinforcement but also of biological interaction and drug delivery performance (Wang et al., 2019; Mariano et al., 2016).

From a biomedical standpoint, the same nanofibrillar network responsible for mechanical cohesion in composites underpins hydrogel formation and moisture retention in wound dressings (Bačáková et al., 2019; Anisa et al., 2021). Jiang et al. (2021, p. 5932) describe that nanofibrillated cellulose “forms a stable three-dimensional network suitable for wound healing applications,” illustrating how nanoscale architecture translates into physiological functionality. In parallel, engineering applications benefit from identical structural features, particularly in stress distribution

and crack-bridging mechanisms within composite matrices (Rendón et al., 2019; Yudhanto et al., 2021).

This convergence suggests that nanocellulose should not be understood as a material with multiple isolated uses, but as a platform technology whose performance emerges from the same underlying structural logic. Such a perspective challenges reductionist approaches that treat biomedical and engineering applications as independent domains. Instead, it invites a unified framework in which molecular architecture dictates multifunctional behavior.

### **Scientific Gaps and Contradictions in the Literature**

Despite the apparent versatility of nanocellulose, the literature reveals significant gaps and internal inconsistencies. One of the most critical limitations concerns the underrepresentation of xerophytic species, particularly those native to the Caatinga biome. While studies on agave and related species are relatively well established, research on *Cereus jamacaru* and other cactaceous plants remains scarce (Orrabalis et al., 2019). This imbalance suggests a geographical and epistemological bias that prioritizes globally cultivated species over region-specific biodiversity.

Another major issue lies in the fragmentation of scientific approaches. Investigations into nanocellulose often remain confined within disciplinary boundaries, with limited dialogue between materials science, biomedical engineering, and environmental studies. As a result, insights into structure–function relationships are frequently partial and context-dependent. For example, while high crystallinity is associated with improved mechanical performance, its implications for biocompatibility are less consistently addressed (Wang et al., 2019).

Contradictions also emerge in the evaluation of functionalization strategies. Alavi et al. (2022, p. 12) state that “bioactive-loaded scaffolds significantly enhance wound healing,” whereas Rodrigues et al. (2025) emphasize the need to carefully assess long-term biological effects of nanoparticle incorporation. These divergent perspectives highlight a lack of consensus regarding the

balance between functionality and safety, particularly in complex biomedical systems.

Such inconsistencies raise fundamental questions about the maturity of the field. Is nanocellulose research progressing toward a unified theoretical framework, or does it remain a collection of isolated experimental efforts lacking integrative coherence?

## **Technological and Industrial Challenges**

The translation of nanocellulose from laboratory-scale innovation to industrial application remains constrained by several technical and economic barriers. One of the most significant challenges concerns the scalability of extraction processes. Techniques such as acid hydrolysis and mechanical fibrillation, while effective at producing high-quality nanomaterials, are often energy-intensive and difficult to standardize across large production volumes (Chaka, 2022; Ghazy et al., 2016).

Variability in raw material properties further complicates this scenario. As demonstrated by Yudhanto et al. (2024), crystallinity and thermal behavior can vary significantly depending on extraction conditions and biomass source, leading to inconsistencies in final material performance. This variability undermines the reproducibility required for industrial applications, particularly in sectors such as construction and healthcare, where material reliability is critical.

Standardization represents another major obstacle. The absence of universally accepted protocols for nanocellulose characterization, processing, and application limits comparability between studies and hinders regulatory approval. Krishnadev et al. (2021, p. 8135) note that “processing conditions strongly influence composite properties,” underscoring the sensitivity of nanocellulose systems to methodological variations.

Economic factors also play a decisive role. Although lignocellulosic biomass is abundant and renewable, the costs associated with processing, purification, and functionalization can offset its advantages. This paradox highlights a central tension in the field: how to reconcile the sustainability of raw materials with the economic feasibility of advanced material production.

## Future Research Directions

The limitations identified in current research open pathways for future investigation, particularly in the development of smart biohybrid systems and multifunctional nanocomposites. One promising direction involves the integration of nanocellulose with responsive materials capable of adapting to environmental or biological stimuli. Such systems could enhance the performance of drug delivery platforms and regenerative materials by enabling controlled and context-sensitive functionality (Patil et al., 2021).

Another critical avenue concerns the design of multifunctional composites that combine mechanical reinforcement with additional properties such as antimicrobial activity, thermal regulation, and environmental responsiveness. The incorporation of plant-derived bioactive compounds, as demonstrated by Firmanda et al. (2022), suggests that natural sources can be leveraged to create hybrid systems with enhanced functionality.

Advances in green processing technologies also represent a priority. The development of low-energy extraction methods and environmentally benign chemical treatments could significantly improve the sustainability profile of nanocellulose production. As noted by Chaka (2022, p. 590), “green extraction methods are essential for sustainable nanocellulose production,” highlighting the importance of aligning technological innovation with environmental responsibility.

Furthermore, expanding research to include underexplored xerophytic species is essential for unlocking new material properties and applications. The structural adaptations observed in plants from extreme environments suggest that these species may offer unique advantages not present in conventional biomass sources (Mateo et al., 2021).

Finally, the integration of nanocellulose within broader systemic frameworks, such as the xerophytic closed-loop biorefinery proposed in this study, represents a critical step toward bridging the gap between material science and sustainability. This approach shifts the focus from isolated

material optimization to the design of interconnected systems capable of addressing environmental, technological, and social challenges simultaneously.

## CONCLUSION

This integrative review consolidates evidence that nanocellulose derived from xerophytic biomass transcends the conventional boundaries of material science, emerging as a multifunctional platform with simultaneous relevance in biomedical systems and sustainable construction. Its physicochemical architecture, particularly crystallinity and aspect ratio, underpins a convergence of properties that enable both biological performance and mechanical reinforcement, revealing a rare alignment between nanoscale structure and macroscale applicability.

The findings reinforce the scientific novelty of approaching xerophytic plants not merely as alternative biomass sources, but as biologically optimized systems shaped by environmental stress. In this sense, the Caatinga biome is repositioned from a marginal ecosystem to a strategic frontier of nanotechnological innovation, capable of informing new paradigms in material design and sustainability.

From a technological perspective, nanocellulose demonstrates remarkable versatility, functioning as a hydrogel matrix, a controlled drug delivery carrier, and a reinforcing agent in composite materials. This adaptability confirms its status as a platform technology, capable of integrating diverse functionalities within a single material framework.

The conceptual proposition of a Xerophytic Closed-Loop Biorefinery represents a critical advancement, shifting the focus from isolated material development to systemic integration between production, application, and ecological regeneration. This model challenges linear production logics and introduces a regenerative approach in which technological innovation is inseparable from environmental sustainability.

Ultimately, the trajectory outlined in this study suggests that the future of advanced materials

lies not only in refining molecular properties, but in redefining the relationship between materials, ecosystems, and society.

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