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Review Article

# Recent advances in nanocellulose-based different biomaterials: types, properties, and emerging applications

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ABSTRACT

The research interest in sustainable and eco-friendly materials based on natural sources has increased dramatically due to their recyclability, biodegradability, compatibility, and nontoxic behavior. Nanocellulose contains chains of glucose residue and is an abundantly available green material. Recently, nanocellulose-based green composites are under extensive exploration and gained popularity among researchers owing to their lightweight, lost cost, low density, excellent mechanical and physical characteristics. These materials have also shown tremendous potential for applications in biomedical and numerous engineering fields. The mechanical properties of these materials play a vital role in effective utilization and their exploration for future applications. This review article comprehensively presents current developments, results, and findings in the arena of green and sustainable materials. Currently, the main problem is the large variability in their properties and qualities. Nanocellulose properties are influenced by various factors, including the fiber type, ecological conditions, manufacturing methods, and any alteration of the fiber surface. Finally, the review incorporates future challenges and opportunities in the field of nano cellulosic materials.



## 1. Introduction

Cellulose, a ubiquitous and natural bio-based polymer material on the earth, is produced from plants, algae, tunicates, and bacteria [1,2]. The total biomass production of the cellulose is $1.5 \times 10^{12}$ tons/year that can be used as a raw material to form biocompatible and eco-friendly products. It is extracted from wool, hemp, flax, cotton, or sisal plants and can be used as a substitute for various polymers owing to lightweight,

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**Nomenclature**

| | |
|---|---|
| ACC | All-Cellulose Composites |
| ACNF | Acetylated Cellulose Nanofiber |
| BC | Bamboo Cellulose |
| BNC | Bacterial Nanocellulose |
| CDA | Cellulose Diacetate |
| CLNP | Corncob Lignin Nanoparticle |
| CNF | Cellulose Nanofiber |
| CNT | Carbon Nanotube |
| DGEBA | Diglyceryl Ether of Bisphenol |
| HDPE | High Density Polyethylene |
| GO | Graphene Oxide |
| L-CNC | Lignin-Coated Cellulose Nanocrystals |
| LED | Light Emitting Diode |
| MAPP | Maleic anhydride grafted polypropylene |
| MC | Methyl Cellulose |
| MCC | Microcrystalline Cellulose |
| MFC | Micro fibrillated Cellulose |
| MWCNT | Multiwalled Carbon Nanotubes |
| NF | Natural Fibers |
| NFC | Nano fibrillated Cellulose |
| NFRPC | Natural fiber reinforced polymer composites |
| OPEFB | Oil Palm Empty Fruit Bunch |
| PEI | Polyethyleneimine |
| PLA | Polylactic Acid |
| PPG | Polypropylene Glycol |
| PVA | Polyvinyl Alcohol |
| PCB | Polysaccharide circuit board |
| PEVA | Poly ethylene-co-vinyl acetate |
| PBAT | Poly butylene adipate-co-terephthalate) |
| RGO | Reduced Graphene Oxide |
| rPP | recycled Polypropylene |
| SCB | Sugarcane Bagasse |
| SPCE | Screen-printed carbon electrodes |
| UV | Ultraviolet |

renewability, natural abundance, biocompatibility, biodegradability, versatility, and excellent adaptability [3–5]. Cellulose and its derivatives have been applied for more than 150 years. It is estimated that the global market share for cellulose fibers will expand rapidly and reach 41.5 billion USD by 2025 [6]. They have recently been used as sustainable materials in various emerging fields like biomedicine, drug delivery, automotive, electronics, and structural engineering applications [7–9] owing to their non-toxicity and ecofriendly nature. Their usage can also be found in energy devices due to their appealing properties [10–12]. They also exist in the composite form containing lignin, polymers, and hemicelluloses. Lignin act as an adhesive media, holding hemicellulose and cellulose [13]. Cellulose is prominent and the principal part of the plant cell divider, allowing the entry of supplements and keeps up the cell shape with significant tensile strength [14,15]. Whereas hemicellulose, a secondary component, acts as a joining media between cellulose and lignin. Furthermore, pectin is also present in plant structures. However, it appears with a minor quantity than the other three components. The purification of cellulose is essential, which will help to eliminate the hemicellulose, lignin, and other small impurities.

Cellulose in composite materials has also become an epicenter of attention and applied in natural fibers (NFs) [16,17]. Its utilization in polymer composites is due to excellent biodegradability, combustibility, non-abrasiveness, low cost, and low density [18]. However, cellulose-based green composites did not achieve industrial realization due to attached anomalies such as poor metallurgical adhesion and water absorption capability. Chemical treatments of the cellulose fibers are the remedies to these problems [19]. Nowadays, scientists are focusing on the extraction of nanocellulose-based materials from cellulose to manufacture nanocellulose-based reinforced green composites for diverse applications.

This study presents a brief knowledge and groundbreaking understanding of cellulose, its primary sources, and the classification of nano cellulosic materials for researchers in this field to unlock advanced applications. Different manufacturing processes and chemical modification techniques of these nanocellulose materials are also illustrated. Recent works (2015–21) about nanocellulose-based composites, their mechanical properties, and their applications are reviewed. The final section provides an insightful overview of the potential challenges and future opportunities in the arena of cellulose-based green composites.

## 2. Cellulose-based natural fibers reinforced composites

Appropriate exploration of easily accessible natural sources becomes an essential factor in establishing a sustainable industry [20–22]. Natural fiber-reinforced composites (NFRCs) fabricated with cellulosic materials have emerged as green and eco-friendly materials [23–26]. NFRCs are easy to manufacture and have minimal effect on the ecosystem compared to conventional composite materials [27–30]. NFRCs are sometimes referred to as "green composites", which are fabricated by adding various types of NFs into biodegradable resins and starch as polymer matrix to improve the mechanical characteristics of the green composites [31,32]. The fabrication of these fibers is similar to the synthetic fibers and uses hand lay-up [33], extrusion [34], resin transfer molding [35], injection molding techniques [36], and compression molding [37]. Furthermore, these composites decrease the overall cost of materials and provide lightweight properties owing to the low density of NFs [38–40]. Classification of cellulose-based materials is presented in Fig. 1. These NFs can be classified based on their source and percentage of hemicellulose and lignin [41,42]. Fig. 2 illustrates the general attributes of cellulose-based materials.

NFRCs can be produced from sustainable cellulose materials that provide environmental and cost-related benefits over conventional composites. However, several critical drawbacks, like higher moisture absorption, inferior mechanical properties, incompatibility with the matrix, poor wetting characteristics, and low thermal resistance [43,44] are associated with these materials that influence their mechanical properties. These drawbacks lead to the failure of the

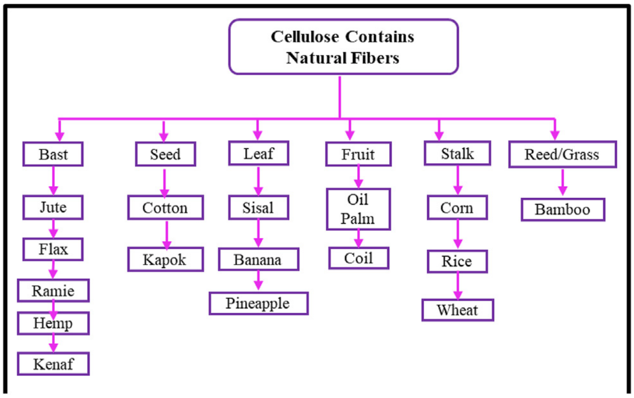


**Fig. 1 – Different types of reinforcing bio fibers containing cellulose.**

green composites [45–47]. Furthermore, it is challenging to fabricate composites due to the inconsistency of the NFs that also limits their industrial utilization. The characteristics of the fibers depend upon the harvesting season that ultimately affects the properties of the composites. Fig. 3 presents the changing percentage of cellulose contents in different NFs. Commercial production of cellulose heavily relies on the harvested source like wood or highly pure origin like cotton. Fig. 4 shows the interest shown by several countries in nanocellulosic materials over the past ten years [48,49].

## 3. Nanocellulose

Nanocellulose is an excellent material that occurs in the form of nano-scaled cellulose fibrils and nanocrystals separated from the cotton linters, plant cell walls, or bacteria through mechanical, enzymatic, or chemical techniques [50,51]. Nanocellulose is extracted from natural cellulose fibers and contains few micrometer lengths and <100 nm diameter. It is mainly classified into three types of nanomaterials; Cellulose nanocrystal (CNC) [52], Nano fibrillated Cellulose (NFC), and Bacterial nanocellulose (BNC) [53].

A brief comparison between the properties of the different types of nanocellulose is provided in Fig. 5. The exceptional properties of nanocellulose include high modulus of elasticity (110–220 GPa), tensile strength (7.5–7.7 GPa), tailored aspect ratios, large specific surface area, easy surface functionalization, tunable crystallinity, high degree of polymerization, and high chemical resistance [54–56]. Due to these unique physicochemical properties, nanocellulosic sustainable materials are gaining importance in aerospace, automobile, packaging industries, energy devices, and other interdisciplinary fields [57]. Furthermore, synthetic materials drastically impact the climate and the consumption of fossil fuels is crucial to consider. Therefore, it is essential to shift towards these sustainable nanomaterials [28,58,59] in upcoming years.

Recent developments in engineering, biomaterials, and other high-end applications demonstrate the importance and capability of different celluloses, especially nanocellulose [60]. These materials have been frequently used in water purification [61], medical services, and veterinary medication [58,62,63]. The dimensions of nanocellulose extracted from different plants and NFs are important because the effectiveness of nanocellulose-based materials depends on the achieved accuracy in nanocellulose dimensions. The dimensions of the isolated nano cellulosic materials obtained from some recent works are summarized in Table 1.

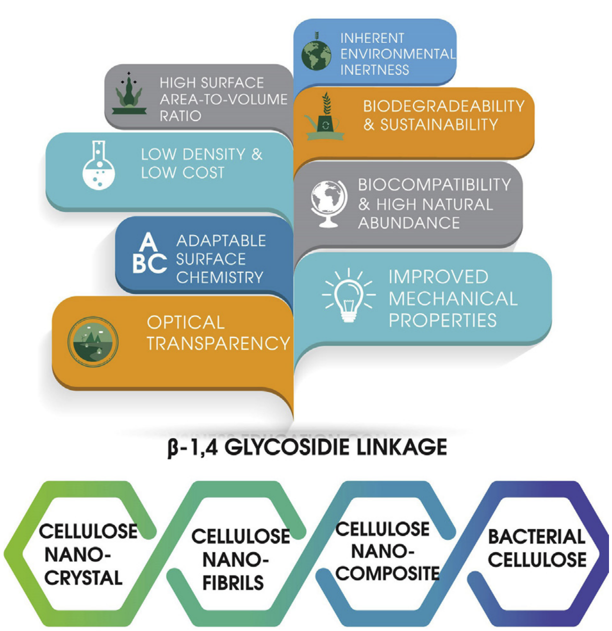


**Fig. 2 – General attributes of cellulose-based materials.**

### 3.1. *Processing and synthesis*

The primary route employed for the synthesis of nanocellulose is acid hydrolysis, including HCl and $H_2SO_4$ acids. Electrostatically stable CNC is produced through acid hydrolysis as a result of sulfuric sulfate half-esters. Sulfate half-esters are formed when the hydroxyl group of cellulose reacts with sulphuric acid. BNC is biosynthesized nanocellulose with an outstanding level of crystallinity [81]. The different processes adopted in the manufacturing of nanocellulose are presented in Fig. 6. After nanocellulose production, various surface treatments [82] are also adopted for improving their physical and mechanical properties. A generic flow chart of obtaining nanocellulose through different procedures is presented in Fig. 7. Among all the surface treatments, the most widely adopted technique is NaOH/urea-based. The various processes involved in NaOH/urea-based treatment are elaborated in Fig. 8.

### 3.2. *Chemical treatments*

The common issue in cellulose-based composites is the hydrophilic nature of the fibers and the hydrophobic nature of the matrix [83,84]. The intrinsic mismatch between these two natures results in poor adhesion at the interface. Different chemical treatments on NFs can decrease their hydrophilic inclination and improve their compatibility with the matrix

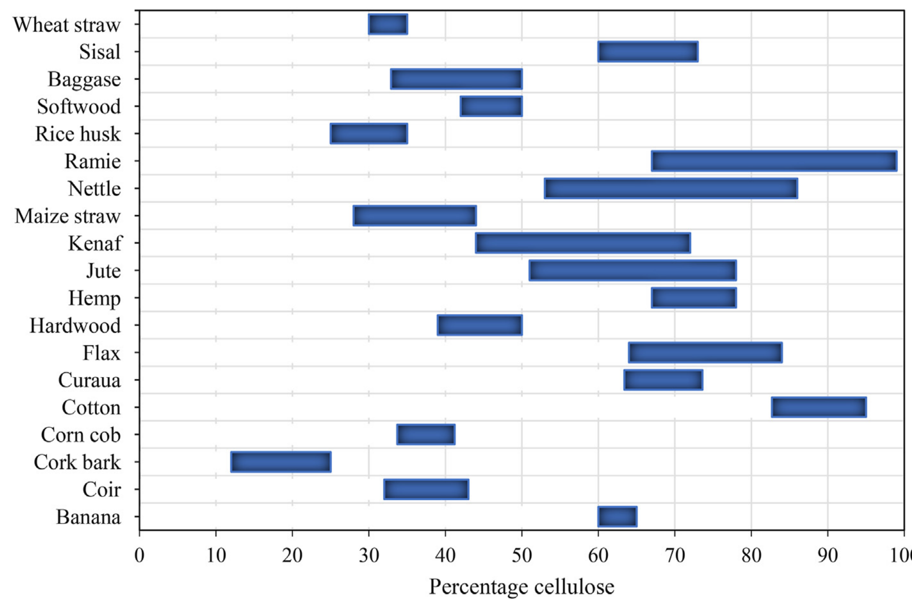


**Fig. 3 – Percentage of cellulose in different natural fibers.**

[85–88]. The most popular treatments on the fiber that have proved their significance in improving different cellulose-based composite properties [89] are; Alkali Treatment [90], Silane Treatment [91], Fungal Treatment, Maleated Couplings Agents, Benzoylation Treatment [92], Peroxide Treatment [93], and Permanganate Treatment [94]. One example related to these chemical treatments on NFCs is elaborated here. Liu et al. [95] studied the influence of the silane treatment on the mechanical properties of corn-stalk fiber-reinforced composites. As shown in Fig. 9, silane treatments produce a rough surface on the corn-stalk fiber surface and thus improves different mechanical properties due to the strong adhesion of fibers with matrix/epoxy.

Mostly different chemical modifications utilized on NFs improve the hydrophobicity [96–98]. The reactions in treatments involve swelling and non-swelling solvents. The resulting reactions from these treatments attach with the hydroxyl group of cellulose [97,99,100] and improve their wettability, tune their microstructure and surface morphology. These changes have a positive effect on the connection between fibers and polymer [4,14,15,101]. Fig. 10 shows the cause-and-effect diagram of chemical treatments on different NFCs.

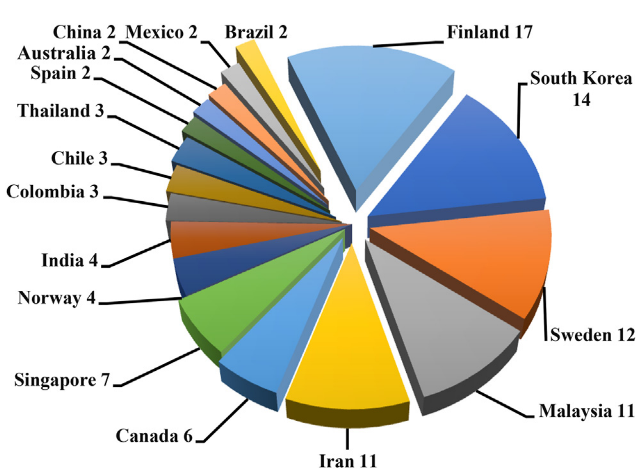


**Fig. 4 – Country-wise interest in nanocellulose.**

### 3.3. *Nano fibrillated cellulose (NFC)*

Numerous researchers [102–105] concentrated on various mechanical instruments, like ultrasonication, steam blast, and microfluidizers for obtaining cellulose [106–108]. Clogging is frequently seen with homogenizers, but it can be resolved by utilizing extruders and high consistency in milling processing, resulting in fiber delamination. Major drawbacks of this technique are high energy requirement and the presence of bigger fragments. The presence of delamination instruments relies upon the final utilization of NFCs [109].

The freeze-drying process is also used for producing permeable cryogels. The primary advantage associated with this technique is low water absorption. On the other hand, the principal disadvantage of freeze-drying is ice crystals during the pre-freezing step. The produced crystal extends and affects the structural qualities of cryogel. This can be reduced using sucrose, or fast freezing methods can also be adopted [110]. Apart from these processing techniques, some surface modification techniques were also applied to the NFCs. The advantages and drawbacks of various surface modification treatments adopted on NFCs are reported in Table 2.

### 3.4. *Cellulose nanocrystals (CNC)*

CNCs possess broader scope of properties, such as enormous surface zone, phenomenal strength, intriguing mechanical properties, and remarkable optical properties. Nano whiskers are sometimes also referred to as CNCs. It possesses higher flexibility than NFC and usually contains 54–88% of crystallinity.

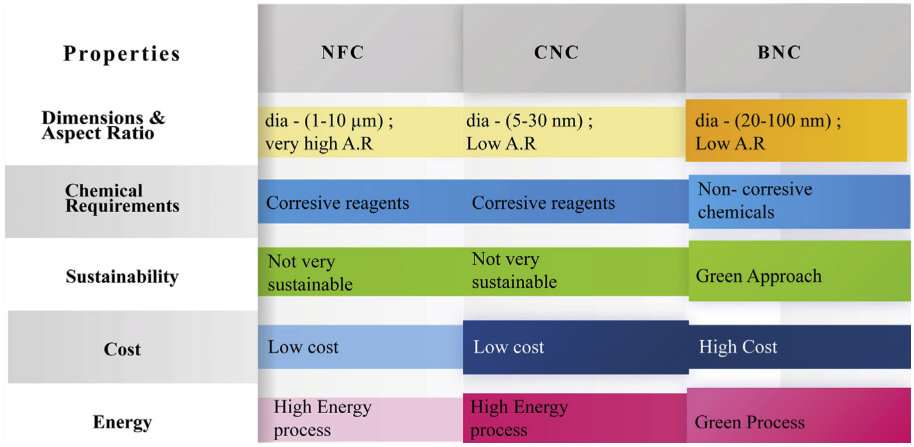


**Fig. 5 – Comparison of different properties against each type of nanocellulose.**

Synthesis of CNC also involves acid hydrolysis technique. CNCs on reaction with naturally available or manufactured polymers yield valuable composites. The physical and mechanical properties of CNCs are improved through different surface modification procedures for their use in composites. Furthermore, these treatments also improve properties like low thickness and high surface zone [115].

### 3.5. *Bacterial nanocellulose (BNC)*

BNCs are produced by utilizing different microorganisms [116]. These microorganisms exhibit great significance because of their fast growth and availability around the year. Generally, two techniques, the static and stirred culture methods, are adopted to produce BNCs. In static culture, BNCs are formed due to the growth of a thick, cowhide-like white BC pellicle at the air-fluid interface [117]. The prime factors for selecting these methods are the final applications of BNC, surface morphology, physical, and mechanical properties of the produced BNC [118]. A summary of some recent studies dedicated to produce different BNCs through different microorganisms is discussed in Table 3.

## 4. Mechanical properties

Nanocellulose-based materials proved to be excellent reinforcing media for improving the mechanical properties of different materials, especially composite materials [127–129]. These materials are most suited in replacements of different synthetic fiber-reinforced composites to fabricate eco-friendly green products [130]. The replacement of synthetic fibers with

**Table 1 – Dimensions of nanocellulose extracted from different sources.**

| Natural Fibers/Plants | Type of Nanocellulose | Dimensions of extracted nanocellulose | | Ref. |
|---|---|---|---|---|
| | | Length | Diameter (nm) | |
| Eucalyptus pulp | CNC | 150 nm | 10–50 | [64] |
| Pinecone | CNF | – | 5–20 | [65] |
| Soybean straw | CNF, CNC | >1 µm | 10 | [66] |
| Hyacinth Fiber (*Eichhornia crassipes*) | CNC | 147.4 nm | 15.6 | [67] |
| Pineapple Leaf Fiber | NC | <(88–1100) nm | 68 | [68] |
| Rice hull | CNF | – | <100 | [69] |
| Banana rachis, kapok, pineapple leaf, coir | CNF | – | 10–25 | [70] |
| Oil Palm trunk | CNF | 170–800 nm | 4–10 | [71] |
| Bamboo | CNC | – | 50–100 | [72] |
| Waste paper | CNC | 100–300 | 3–10 | [73] |
| Banana Peels | CNF | 455 nm | 10.9 | [74] |
| Palm Residue | Coir NC | – | 108 | [50] |
| | Fronds NC | – | 90 | |
| Coir Fiber | CNF | – | 37.8 | [75] |
| Jute Fiber | CNF | – | 50 | [76] |
| Beer industrial residues | NC | – | 73–145 | [77] |
| Coconut residues | CNF | – | 70–120 | [78] |
| Silkworm silk fibers | CNF | – | 0.1–0.4 | [79] |
| Flax | CNC | 57 nm | 6 | [80] |
| Cotton | CNC | 68 nm | 8 | |

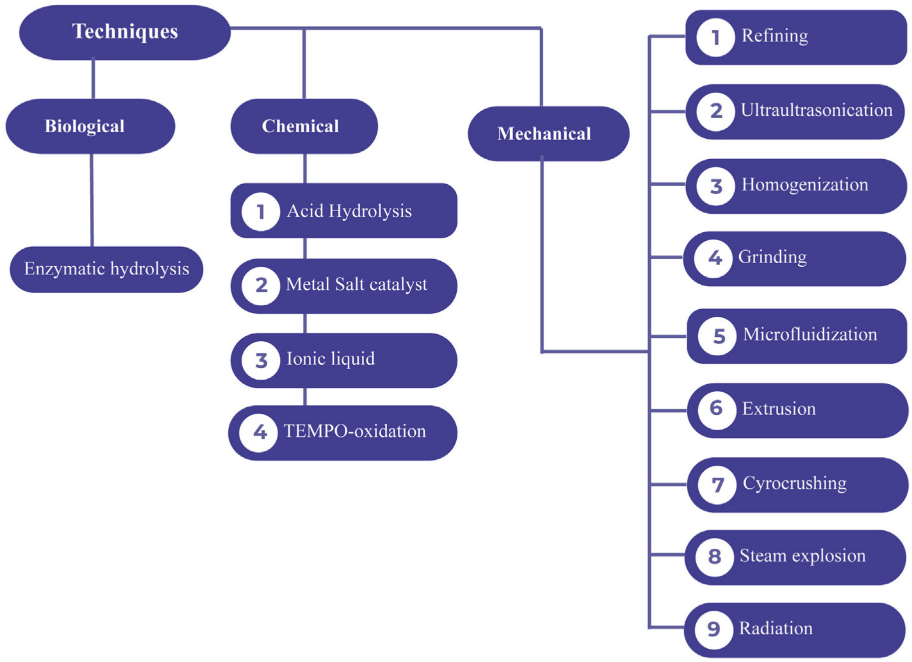


**Fig. 6 – The different processes adopted in the manufacturing of nanocellulose.**

these nanocomposites in the industries is due to the low density and cost, nobler mechanical properties and thermal insulation, less environmental impacts combined with sustainability trends. Furthermore, the mechanical and physical characteristics of the nanocellulose-reinforced composites are comparable with the properties of the synthetic fibers. Traditionally glass, carbon, and aramid fibers are utilized in fiber-reinforced composites. For example, glass fiber possesses elastic modulus between 70 and 110 GPa and a density of 2.5 g/cm$^3$, and aramid fiber possesses modulus between 63 and 67 GPa with a density of 1.4 g/cm$^3$ [28]. Therefore, when materials are required to be chosen based on the modulus of elasticity and weight, nanocellulose is an excellent choice for this scenario having roughly 65 J/g for NFC and 85 J/g for CNC. In comparison, traditional materials like steel provide only 25 J/g. Nowadays, these materials have also been utilizing in many structural applications as a substitute for steel owing to their excellent mechanical properties [131].

Nanocellulose-based composites exhibit excellent mechanical properties due to these nanofillers' stiffening influence, especially at a lower concentration. It results in a large specific surface area that provides excellent interaction between the polymer matrix and nanocellulose. The distribution and dispersion of the nanomaterials in the hydrophobic matrix must be uniform to ensure significant force transfer in the nanocomposites. Furthermore, the homogeneous dispersion and metallurgical interaction between the polymer matrix and nanocellulose produce nanocellulose composites of the properties that lie between the properties of polymer matrix and cellulose. Ghasemi et al. [132] developed CNF-based PLA composites, and microscopic analysis depicted excellent dispersion of the CNF in the polymer matrix. As a result, significant mechanical and thermal properties were achieved. Therefore, an optimum concentration of nanocellulose promotes dispersion and distribution in the polymer matrix, providing better mechanical interlocking and interfacial strength. In another study, Carrillo et al. [133] obtained dispersion in the non-polar matrix using the proposed double emulsion technique. The authors balanced the nanocellulose with the organic polymer matrix in a double emulsion (water-in-oil-in-water) solution. It avoided the drying of the dispersion of nanocellulose before the processing. In this way, the microstructure and mechanical properties of the nanocomposites can be tuned by managing the ionic strength of nanocellulose in the dispersion.

Recently, the attention of the manufacturers and consumers has been diverted to develop green composite by employing cellulosic materials as reinforcing agents [10]. Numerous researchers reported that the addition of NFs, NFC, and CNC into the polymer matrix significantly improved the mechanical properties of the composites. To replace the glass fiber sheet of the vehicles, Wu et al. [134] fabricated kenaf fiber-reinforced composites using the vacuum bag resin transfer molding technique. The results revealed that these composites exhibited excellent mechanical characteristics and minimized energy consumption, contributing to promoting a sustainable environment. Morelli et al. [135] found that the CNC incorporation increased tensile strength and elastic modulus of the polybutylene adipate-co-terephthalate (PBAT). In another study, Tan et al. [136] investigated the influence of the addition of CNC in the polyethylene-co-vinyl acetate polymer matrix (PEVA), and the results indicated significantly improved mechanical properties of the nanocomposites. Likewise, Spinella et al. [137] tried

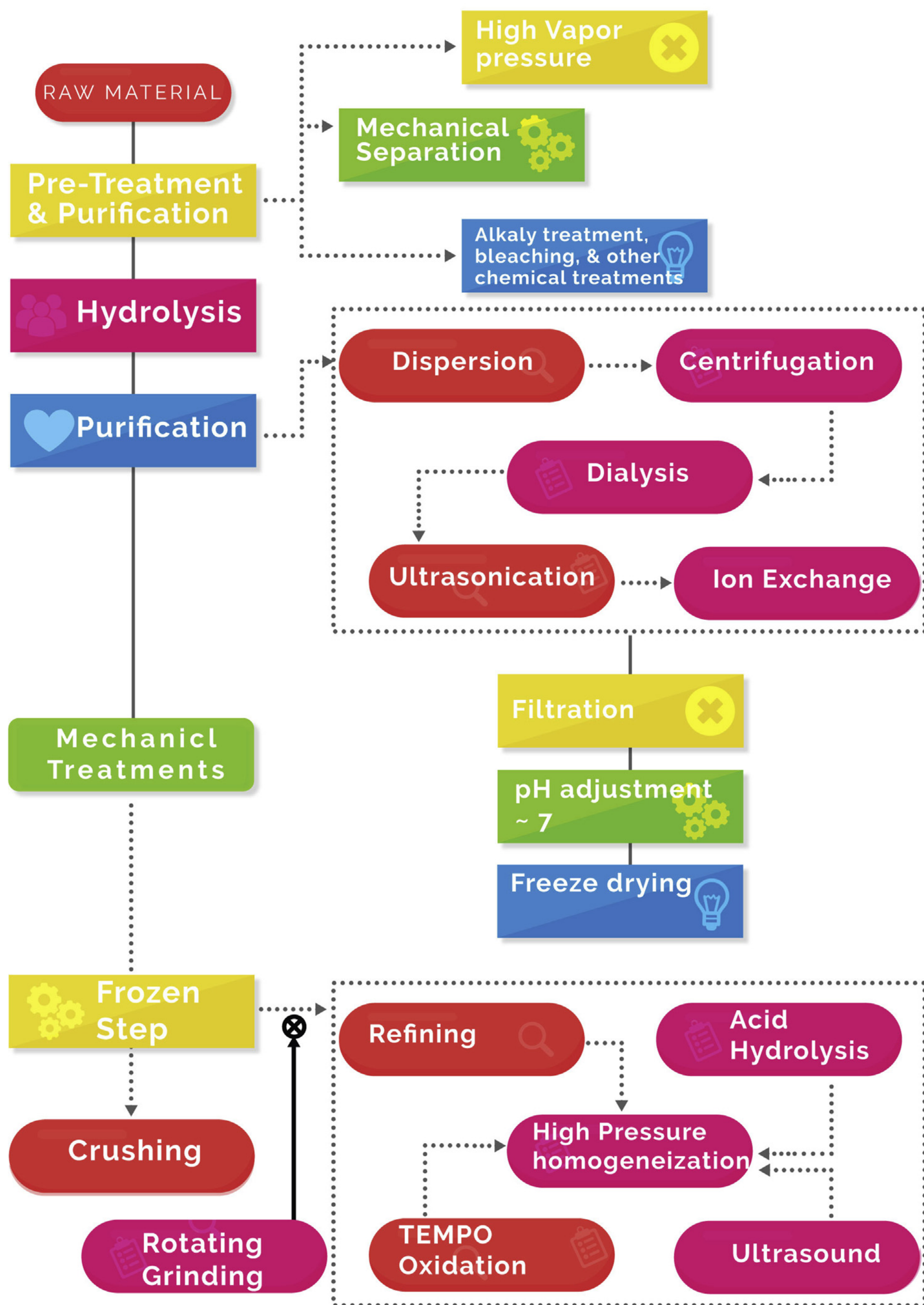


**Fig. 7 – Generic flow charts of obtaining nanocellulose through different steps.**

to improve the mechanical characteristics of the PLA by adding CNC and found that both loss modulus and storage modulus of the nanocellulose-based composites were enhanced in comparison to pure polymer. The method of obtaining nobler mechanical properties with the incorporation of nano cellulosic materials depicted that these nanocomposites can be employed as potential replacements of synthetic fiber-reinforced composites in the engineering and material science fields.

To summarize, the type of fibers, dimensions, microfibril orientation, the volume contents of the nanocellulose materials in the fibers, chemistry with matrix, surface, and chemical treatments are critical parameters that influence the overall mechanical properties of nanocellulose materials [138–140]. Some recently reported works on the mechanical characterization of different nano cellulosic composite materials treated with different chemicals are also summarized in Table 4.


**Fig. 8 – Different processes involved in NaOH/urea-based treatment.**

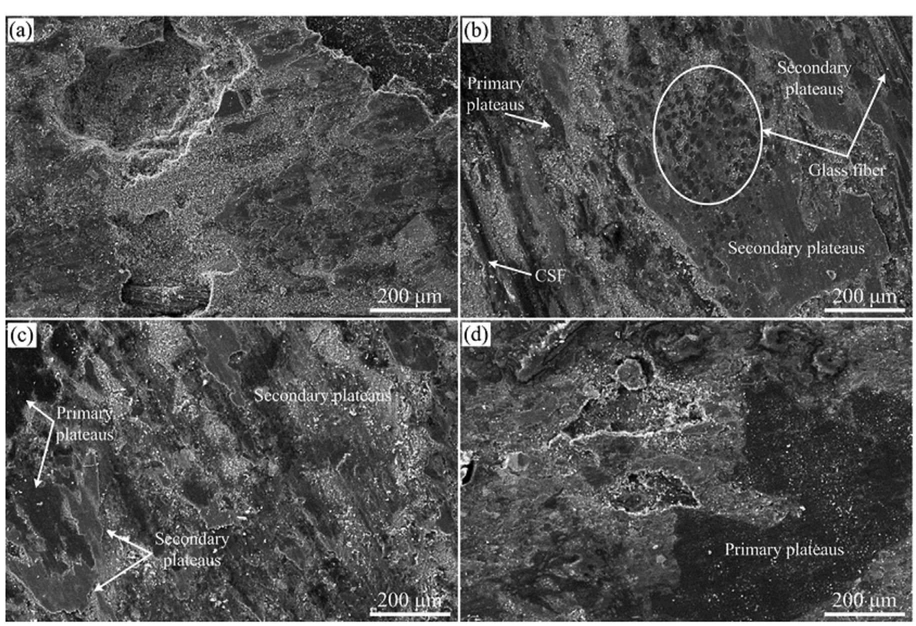


**Fig. 9 – Micrographs of the corn stalk fibers composite with different percentage of silane treatments (a) 1% (b) 5% (c) 9% (d) 13% [95] (Images reproduced with permission from Elsevier).**

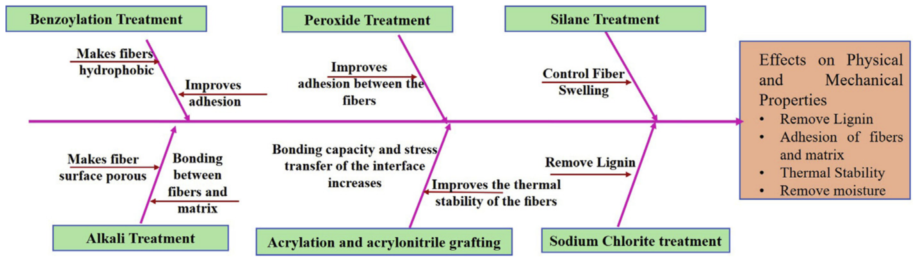


**Fig. 10 – Cause and effect diagram of different chemical treatment procedures on NFs.**

**Table 2 – Advantages and drawbacks of some treatments used on NFC.**

| Surface Treatment | Improvements | Drawbacks | Ref. |
|---|---|---|---|
| Polymer Grafting | Inherit the NFC along with some mechanical properties | The organic solvents use in this method and have negative effects on the environment. | [48] |
| Plasma Discharge | Enhance the carboxyl and carbonyl groups, and the quantity of oxygen increases at nanocellulose surface. | Expensive experimental setup is required (like arc discharge) and parameters like high frequency and low power are difficult to achieve. | [111] |
| Physical adsorption | Improves the bonding process between nanocellulose and polymers. | Large water is consumed, and wastewater contains many hazardous materials. | [112] |
| Grafting (UV based) | Environment-friendly technique as no organic solvent is consumed. | Highly labor skilled is required. Color fading and chromatic homogeneity are largely influenced. | [113] |
| Silane based Treatment | Improves the hydrophilic nature of fibers. | Sometimes different mechanical properties like elongation are not improved through this technique. | [114] |

**Table 3 – Recent work on BNC production through different microorganism.**

| Methods | Microorganism | Chemical Process Adopted | Time | Temperature | Final BNC amount (g/L) | Ref. |
|---|---|---|---|---|---|---|
| Static Culture | *G.xylinus CH001* | – | 5 days | 28 °C | 0.66 | [119] |
| Static Culture | *Komagataeibacter saccharivorans* | d-$H_2O$ & NaOH | 7 days | 28 °C | 3.9 | [120] |
| Static Culture | *K. medellinensis* | Citric Acid | 12 days | – | 5 | [121] |
| Static Culture | *Yeast (SCOBY)* | NaOH treated | 20 days | 30 °C | 29.2 | [122] |
| Static Culture | *K. medellinensis* | Cross couplings Reactions | 8 days | 28 °C | 6 | [123] |
| Static Culture | *K. xylinus BPR 2001* | – | 9 days | 30 °C | 6.4 | [124] |
| Static Culture | *yeasts (SCOBY)* | NaOH treated | 20 days | 30 °C | 60 | [125] |
| Stirred Culture | *G. hansenii CGMCC 3917* | – | – | 30 °C | 7.02 | [126] |

## 5. Applications of nanocellulose

The nanocellulosic materials are used as packages on different food products due to their bio-friendly properties [164,165]. For example, low absorbency of cellulose and the ability to produce a thick percolating network of hydrogen bonds are attractive characteristics for the filtration process [166]. Two important areas are primarily focused on this particular application. One is oxygen (gas) permeability [167,168], and the second is water transmission in vapor form [169]. The low porosity and surface harshness of NFCs make them suitable materials for the printing of conductive tracks.

### 5.1. *Flexible electronics*

In this modern world, engineering and extensively used different equipments are going through a widespread change from rigid counterparts to flexible electronics, owing to their numerous benefits over rigid electronics, for example, mechanical flexibility, durability, and lightweight components [170–172]. A lot of research has been conducted in the past that demonstrates flexible electronics as a high-performance competitive device as compared to rigid electronics (Fig. 11). The equipments with mechanical flexibility, lower creation cost, and feasible manufacturing ultimately determine their efficiency and durability [174–176]. Nanocellulose-based films [177] are highly emerging because of their several merits, making the current electronics move forward towards high performance and multi-functional applications. Moreover, the features like low cost, portability, biodegradability, and disposability are attracting other applications such as biomedical, aeronautical, and energy conversion devices [169,178]. Nanocellulose-based materials are applied to develop the devices such as solar cells, transistors, touchscreens, supercapacitor applications [179].

**Table 4 – Some recent work (2015–20) on the Cellulose-based natural fibers/nanocellulose reinforced composites.**

| Cellulose containing natural fibers reinforced composites | Matrix Source | Adopted Chemical Treatments | Mechanical characteristics | | | Important Finding | Ref. |
|---|---|---|---|---|---|---|---|
| | | | Tensile Strength (MPa) | Flexural Strength (MPa) | Impact Strength | | |
| MFC | PPG | Silane | 42.7 | – | – | The tensile strength is increased up to 70%. | [141] |
| Wood fiber | PLA | – | 65 | 93 | 24 J/m | Multi-functional bio-additive improved the mechanical properties. | [142] |
| Cotton linters | – | NaOH/urea (Solvent) | 122 | – | – | The addition of embedded CNTs generates high electrical conductivity. | [143] |
| Wood pulp-based ACC | – | NaOH/urea (Solvent) | 45.9 | – | – | Tensile strength improved more than ten times with a short solvent treatment. | [144] |
| CNF | Epoxy/DGEBA | – | | | | The addition of CNFs improves thermal as well as storage and loss modulus of these nanocomposites drastically. | [145] |
| *Salix psammop il* powder | – | – | | | | The tensile strength improved to 304.6 MPa with 10 wt.% MWCNTs, which was nearly 106.8% higher than that of MWCNT/cellulose fibers with a similar quantity of MWCNTs. | [146] |
| Pulp softwood craft fibers | – | NaOH solution | | | | The produced ACC cryogels and aerogels shows improved compressive modulus and absorbed energy up to 40%. Strain increased. | [147] |
| Cellulose nanofibrils | – | – | | | | The cellulose nanofibrils lessens the syneresis of the alginate gels and enhances its compression against deformations. | [148] |
| MCC | rPP | MAPP | 28 | – | 7.5 kJ/$m^2$ | Mechanical properties were improved with MAPP. | [36] |
| MCC | – | Citric acid | 2.25 | 7.8 | | The maximum mechanical properties were attained at 5% citric acid concentration. | [149] |
| MC | – | PEI | 10 | | | A good match between theoretical and experimental results shows uniform dispersion of PEI-RGO in MC. | [150] |
| MFC | – | NaOH | | | | The uniform distribution of NFC improves its mechanical properties. | [151] |
| SCB | HDPE | Zirconium oxide | 15.7 | 18.6 | 38.9 kJ/$m^2$ | Influential effects of mentioned treatment on SCB mechanical properties. | [152] |
| Cotton linters | – | NaOH/urea | | | | At 5% wt. these redacted GO composite behaves as multi-functional sensor material. | [153] |
| L-CNCs | PLA | – | | | | A uniform dispersion of L-CNCs and an equal crystallinity of PLA improves thermo-mechanical properties. | [154] |
| CNF | – | Acetylation | 14.7 | | | The ACNFs lowers the degradation rate of CNF as a result of fungal degradation. | [155] |
| BC, CNF | PVA | Acetylation | 43 | | | These CNFs exhibit good visible light transmittance along with improved mechanical properties. | [156] |
| MCC | PVA | NaOH/Urea | | | | The PVA based MCCs has improved fracture toughness of 44.3 MJ/$m^3$. | [157] |
| MCC | Epoxy | Alkali | 50 | 70 | 12 kJ/$m^2$ | The alkali treatment increases the mechanical properties of MCC. | [158] |
| CLNP | – | – | | | | The manufactured composites films possess a high UV resistance at 5% wt. of CLNP. | [159] |
| SCB, CNC | k-carrageenan | Alkali | 85 | | | The inclusion of CNC reduced the light transmittance capacity but improved the mechanical properties. | [160] |
| CNF | – | – | 72.3 | | | Addition of graphene in CNF matrix improves its tensile strength while maintaining good flexibility. | [161] |
| Jute, kenaf, hemp fibers | Epoxy Amite | – | | | | The hybridization of NFs improves the mechanical properties. | [162] |
| CDA | – | Alkaline | 45 | | | The ACC films produced from cellulose II as a result of alkali treatment on CDA and NFCs conversion. | [163] |

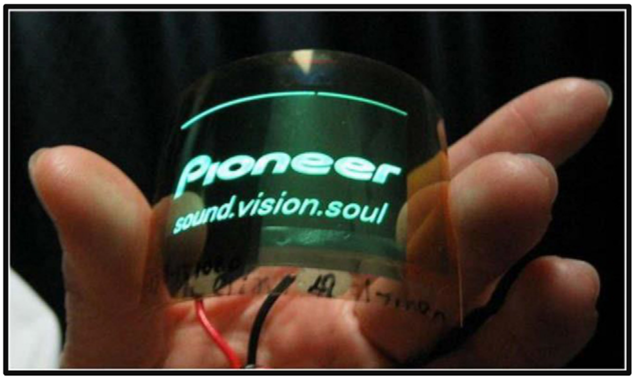


**Fig. 11 – Flexible display on CNF substrate [173] (Adopted with permission from Elsevier).**

### 5.2. *Skin electronics*

One of the essential applications of nanocellulose-based materials is skin electronics that exhibits flexible, and self-healing characteristics, and can be biocompatible with human skin tissues. It has enormous applications in the biomedical sector, such as medical diagnostics and biomimetic prosthetics [180]. Daniele et al. [181] proposed a conformal electronic decal that was based on a polysaccharide circuit board (PCB) incorporated with thin nanocellulose-based film and water-soluble pullulan layer that showed not only the good mechanical and thermal properties but also exhibited high water vapor transmission rates, which is a remarkable property for skin electronics. Nanocellulose-based films [182] have also revealed their applications in diagnosing neurological disorders because of their excellent biocompatibility, wettability, and good surface roughness at the nanoscale [122,178].

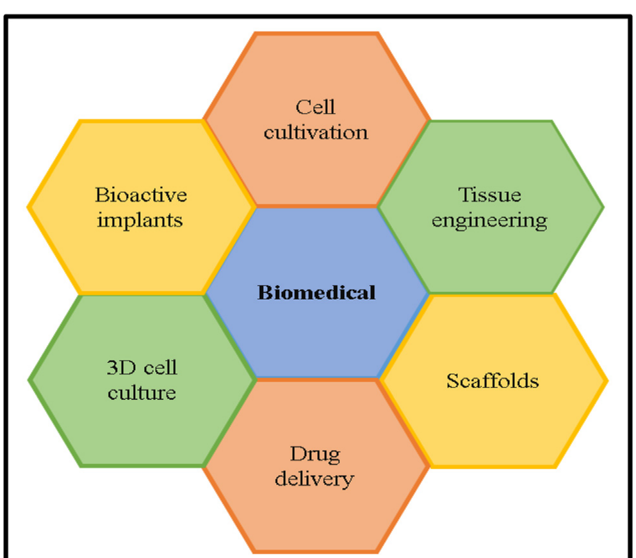


**Fig. 12 – Pictorial representation of Biomedical Applications of Nanocellulose.**

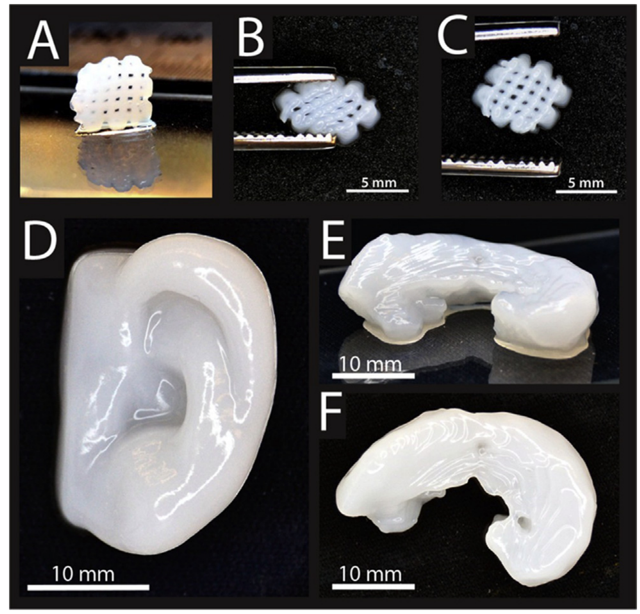


**Fig. 13 – Different 3D printed nanocellulose–alginate scaffolds. "(Reprinted with permission from [208]. Copyright 2021 American Chemical Society)".**

### 5.3. *Photodetectors*

Photodetectors are the most used elements for sensing and monitoring the different motions and environmental changes. However, it remained challenging to produce a photodetector of non-toxic, transparent, and biodegradability features [183]. Park et al. [184] proposed pure nanocellulose-based transparent, non-toxic, and high-performance films, which displayed good electric properties, including the saturation mobility of 1.4 $cm^2V^{-1}s^{-1}$. It also exhibited excellent electrical features under the mechanical bending test. In this way, nanocellulose-based films can be applied as substrates for environment-friendly sensor systems.

### 5.4. *Water treatment*

Water pollution is causing severe threats to human lives and other living organisms because of the rapidly growing population, industrial and agricultural activities. Several engineering tools/equipments have been introduced to purify this polluted water, including reverse osmosis (RO) membranes, solar evaporation, and filtration through the membrane [185]. From all of these, one of the most used filtration techniques is membrane filtration which is used to remove the pollutants from the contaminated water owing to its low environmental concerns, high efficiency, chemical stability, and durability [186]. Furthermore, nanocellulose-based films are the most suitable and feasible source of purification due to their inherent properties such as sustainability, less costly, wider availability, hydrophilicity, eco-friendly, and can be redeveloped [187]. Moreover, these nanocellulose-based membranes are attractive materials for water treatment because of their capacity to modify pore

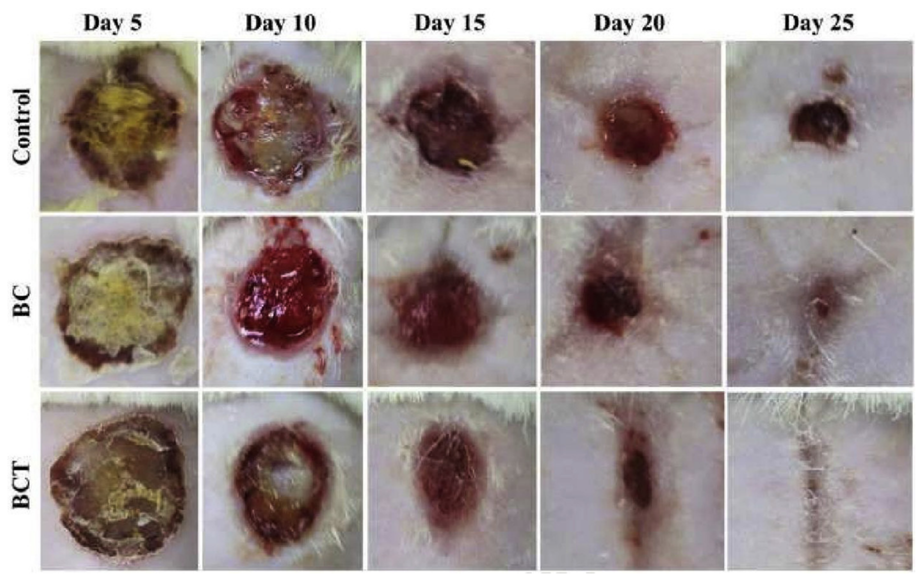


**Fig. 14 – Effect of BNC and BCT hydrogels on wound healing on different day 5, 10, 15, 20, and 25 [209]. (Adopted with permission from Elsevier).**

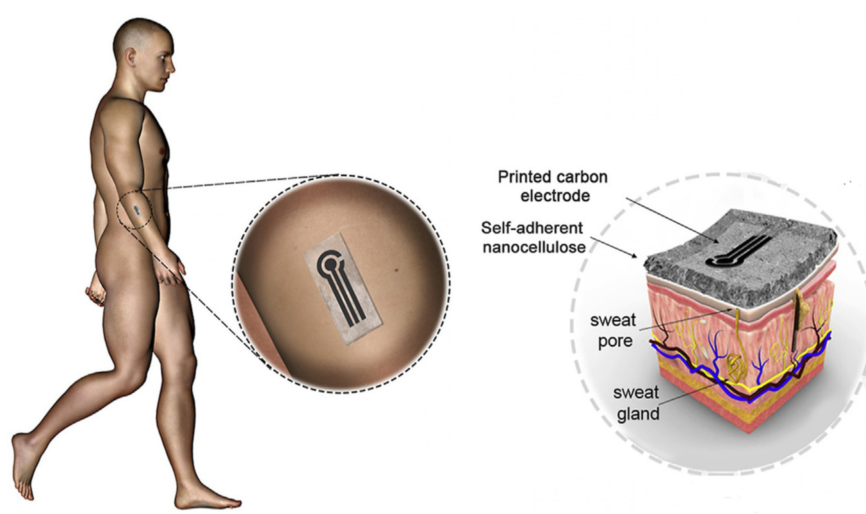


**Fig. 15 – Pictorial depiction and schematic layered diagram of SPCEs on BNC substrate for electrochemical biosensing application [210]. (Adopted with permission from Elsevier).**

size, mechanical properties, water flux, adsorption capacity, and operating pressure [188,189].

Different types of nanocellulose-based membranes are available with distinct pore sizes. Here, only two types of membranes for water treatment are discussed: pure nanocellulose made membranes and composite membranes containing a significant portion as nanocellulose and minor portion of other relevant materials. Mihranyan et al. [190] developed a membrane using CNFs extracted from Cladophora algae to eliminate the virus from contaminated water. These CNFs can filter 80–120 nm-sized viruses (swine influenza and xenotropic murine leukemia) with high efficiency. High-performance composite membranes have also been introduced with reinforcement of inorganic and metallic particles. For dye degradation, highly efficient nanocellulose-based composite membranes were developed by introducing graphene oxide (GO) into the BNC matrix, followed by in situ syntheses of palladium nanoparticles on the GO flakes. Pd/GO/BNC-based layered membranes enhanced the contact and interaction between dye contaminants and catalytic Pd NPs, thus, maximized the dye degradation performance while filtrating the water [191].

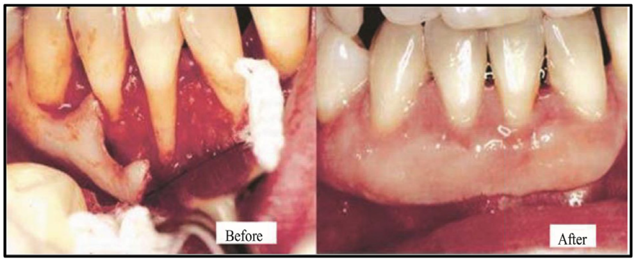


**Fig. 16 – BNC effectively utilized in dental tissue regeneration (a sample pic of 39-year-old female patient) [211].**

### 5.5. *Biomedical applications*

Nanocellulose is a promising biomaterial for different medical applications, owing to its biocompatibility [192], low cytotoxicity, distinct shape, surface science, rheology, and crystallinity [193–195]. The cytotoxicity of these materials relies upon molecule size, surface science, and impeccability of the manufacturing process. Furthermore, drug delivery [196], tablet coatings [197,198], and protein immobilizations [126] are also the other research hotspots in which these nanocellulose-based materials can be effectively utilized [199]. Furthermore, these materials also gain importance in health-caring products due to their significant mechanical properties, nano-scaled fibrous interlinked structure, and natural availability. These features have attracted researchers to develop their applications in different biomedical material synthesis, such as nanocellulose in hydrogels, scaffolds, threads, bioactive implants, drug delivery, cell cultivation, and tissue engineering (Fig. 12).

Efforts have been made to synthesize biomaterials with osteoconductive and osteoinductive properties, similar matrix structure as natural extracellular to build stronger cell–material interaction for bone engineering. In this scenario, bacterial cellulose contributes as an effective biopolymer and is used for tissue engineering applications due to its excellent mechanical strength. Among all the types of nanocellulose, BNCs are considered the most important in biomedical applications [138] due to their excellent biocompatibility, thus suited for many applications like scaffold [200], tissue engineering [201], and membranes. Antimicrobial treatment, auricular cartilage regeneration [202,203], and blood vessel replacements [204] are by far the essential areas of BNCs applications [205–207]. For example, Markstedt et al. [208] produced human chondrocytes within an ear-like shape, as depicted in Fig. 13.

Wounds can cause a risk of infection and need to be treated for proper healing to avoid serious health problems. These

**Table 5 – Applications of different nanocellulose in various biomedical and other engineering fields.**

| Applications | Nanocellulose Forms | | | | Ref. |
|---|---|---|---|---|---|
| Electronics Devices | CNF | 0D, 1D, 2D | – | – | [180,217] |
| Tissue Engineering | – | – | – | – | [218] |
| Medical/Pharmaceutical Industries | – | CNC | – | – | [219] |
| Energy-based devices | CNF | – | CNC | – | [180,220] |
| Biosensors | CNF | – | CNC | – | [183,221] |
| Self-Heating Polymer films | CNF | – | – | – | [222] |
| Water Treatment | – | – | CNF | – | [180] |
| Rubbery Materials | CNF | CNC | – | – | [223] |
| Optical Devices | CNF | – | – | – | [224] |
| Food Industries | – | – | CNC | – | [225] |
| Agriculture Industries | – | CNF | CNC | – | [57] |
| Package Industries | NC | – | CNC | – | [226–228] |
| Hydrogels | – | BNC | CNC | – | [129,229] |
| Automotive Windows | – | – | CNC | – | [230] |
| Wound Healing/Diagnosis | CNF | | | | [183,231] |
| Biomedical Devices | CNF | | | | [232] |
| Barrier Films | | CNF | | | [233] |
| Continuous Papermaking | CNF | | | | [234] |
| Coatings Materials | CNF | | CNC | | [235] |
| Aerogels | ACC | | CNC | | [147,236] |
| Ballistic Protection | BC | CNFs | CNC | | [178] |
| Cryogels | NFC | | | | [237] |
| Biocomposites | BC | | | | [238] |
| Textile industries | Plant Stem (giant reed and Dutch rush) with different polymer materials | | | | [239] |
| Aerospace structure | BC | | | | [240] |
| Self-cleaning Materials | Superhydrophobic Cellulose | | | | [241] |
| Viscosity modifiers | CNF | | | | [242] |
| Antibacterial Materials | MFC | | | | [243] |
| Rheology modifiers | CNF | CNC | | | [244] |
| Porous Materials | | NFC | | | [245] |
| As catalysts | Ethylenediamine-functionalized nanocellulose | | | | [246] |
| Hygiene products | OPEFB Nanocellulose | | | | [247] |

different nanocellulose-based materials are effective for wound healing applications. For example, Jiji et al. [209] proposed thymol enriched bacterial cellulose hydrogel for a third-degree burn. This study revealed that these bacterial cellulose hydrogels (BCT) have an exceptional biocidal activity for burn-related pathogens and improve this type of wound (Fig. 14). Furthermore, these hydrogels enabled the development of fibroblast cells bearing low toxicity and enhanced cell viability than traditional bacteria cellulose (BC) technique.

BNC is an excellent skin substitute, usually utilized for wound dressing, and offers extraordinary substrate for wearable sensors. Silva et al. [210] proposed a comprehensive study on skin-adherent biosensors to detect metal ions in human sweat and urine. The sensing unit is composed of screen-printed carbon terminals (SPCEs) on BNC. These prepared SPCEs were utilized to identify the poisonous metals cadmium ($Cd^{2+}$) and lead ($Pb^{2+}$) with an accuracy of detecting 1.01 and 0.43 μM, individually, which is adequate for detecting these metals ions in the human body (Fig. 15). In the form of the *Gluconacetobacter xylinus* strain, BNC is effectively used to regenerate dental tissue [211] (Fig. 16). Furthermore, NC such as Gore-Tex® and Gengiflex® have been observed as promising materials within the dental industry [212].

New nanocellulose-based threads have been synthesized that exhibited biocompatibility with human stem cells to accelerate the healing procedure [213]. These threads are generally prepared with the patient's cells one week before human surgery to avoid the risk of human immune reaction [214]. Nanocelluloses have also been used in polyvinyl alcohol-based hydrogels for ophthalmic applications as these composite materials are mechanically strong regardless of their softness and flexibility [215,216].

To summarize this, nanocellulose is extensively utilized in many applications of engineering and biomedical fields. The nanocellulose is produced from waste fruit and organic products. Researchers concentrate further on the extraction, surface modifications and explored further applications of nanocellulose. A summary of previous works on exploring different applications of nanocellulose is summarized in Table 5.

## 6. Conclusion

In this study, nanocellulose-based materials are discussed based on the recently published studies, mostly from 2015 to 2021. The major three types are CNCs, CNFs, and BNCs; in terms of synthesis, different surface characterization techniques and emerging applications in various fields are summarized. The fundamental mechanisms behind these three types are also highlighted. The different intrinsic characteristics of nanocellulose-based composites can be improved considerably by different manufacturing methods and by incorporating efficient materials with nanocellulose. For instance, by adding different nanoparticles like MWCNTs, the mechanical characteristics of nanocellulose based composites have been improved. Furthermore, chemical treatments also provide the improved mechanical properties of nanocellulose. It is worth mentioning that there is ever-growing interest for researchers in developing a strong relationship between the different properties like fibril morphology, crystallinity, hydrophilic capacity, and mechanical properties (elasticity, elongation, thermal stability, and surface roughness). Among all the types of nanocellulose, BNCs and NFCs have strong potential to reinforce nanocellulose-based composite materials. To our best knowledge, a maximum young's modulus of 21 GPa and the maximum strength of 320 MPa were found in tensile property characterization of these nanocellulose composites, which have been achieved so far. One of the major issues that need to be sorted in nanocellulose composite is the poor dispersion of the nanofillers in the polymer matrices. It is concluded that cellulose should be considered the main component in polymers. Industrial-scale production of nanocellulose can be possible from cellulose and subsequently their utilization in engineering and medical applications.

## 7. Future challenges and opportunities

Although considerable improvements in nanocellulose-based materials properties are reported. However, removing different substances to improve their performance and recycling issues are still the major concerns associated with nanocellulosic materials. Future investigations on nanocellulose-based materials must consider various aspects like biomimetics, numerical models, artificial intelligence (AI), and machine learning-based algorithms to address the current difficulties. The novel manufacturing routes like additive manufacturing or 3D printing should also be considered for uniform and on-demand utilization of nanocellulose. 3D printing based novel processes must be explored to produce nanocellulose, which should be technically feasible for large-scale production. These considerations will further empower the researchers to get better-functionalized nanocellulose materials and their composites in the future. With the significant advancements in multi-disciplinary areas, nanocellulose-based composites will show improved characteristics. Furthermore, these materials should have considerably low environmental impacts. These research gaps will lead towards a new research area of sustainable nanocellulose for high-performance and advanced applications.

## Data availability

Data sharing does not apply to this article as no datasets were generated or analyzed during the current study.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## REFERENCES


[1] Zainal SH, Mohd NH, Suhaili N, Anuar FH, Lazim AM, Othaman R. Preparation of cellulose-based hydrogel: a review. J Mater Res Technol 2021;10:935–52. https://doi.org/10.1016/J.JMRT.2020.12.012.

[2] Tuan Rohadi TN, Ridzuan MJM, Abdul Majid MS, Khasri A, Sulaiman MH. Isolation and characterisation of cellulose from cortex, pith and whole of the Pennisetum purpureum: effect of sodium hydroxide concentration. J Mater Res Technol 2020;9:15057–71. https://doi.org/10.1016/J.JMRT.2020.10.102.

[3] Nasrollahzadeh M, Sajjadi M, Iravani S, Varma RS. Starch, cellulose, pectin, gum, alginate, chitin and chitosan derived (nano)materials for sustainable water treatment: a review. Carbohydr Polym 2021;251:116986. https://doi.org/10.1016/j.carbpol.2020.116986.

[4] Zhou L, Ke K, Yang MB, Yang W. Recent progress on chemical modification of cellulose for high mechanical-performance Poly(lactic acid)/Cellulose composite: a review. Compos Commun 2021;23:100548. https://doi.org/10.1016/j.coco.2020.100548.

[5] Kotcharat P, Chuysinuan P, Thanyacharoen T, Techasakul S, Ummartyotin S. Development of bacterial cellulose and polycaprolactone (PCL) based composite for medical material. Sustain Chem Pharm 2021;20:100404. https://doi.org/10.1016/j.scp.2021.100404.

[6] Gwon S, Shin M. Rheological properties of cement pastes with cellulose microfibers. J Mater Res Technol 2021;10:808–18. https://doi.org/10.1016/J.JMRT.2020.12.067.

[7] Chen X, Wang K, Wang Z, Zeng H, Yang T, Zhang X. Highly stretchable composites based on cellulose. Int J Biol Macromol 2021;170:71–87. https://doi.org/10.1016/j.ijbiomac.2020.12.116.

[8] Lu Z, Huang J, Songfeng E, Li J, Si L, Yao C, et al. All cellulose composites prepared by hydroxyethyl cellulose and cellulose nanocrystals through the crosslink of polyisocyanate. Carbohydr Polym 2020;250:116919. https://doi.org/10.1016/j.carbpol.2020.116919.

[9] Thinkohkaew K, Rodthongkum N, Ummartyotin S. Coconut husk (Cocos nucifera) cellulose reinforced poly vinyl alcohol-based hydrogel composite with control-release behavior of methylene blue. J Mater Res Technol 2020;9:6602–11. https://doi.org/10.1016/J.JMRT.2020.04.051.

[10] Abdul Khalil HPS, Bhat AH, Ireana Yusra AF. Green composites from sustainable cellulose nanofibrils: a review. Carbohydr Polym 2012;87:963–79. https://doi.org/10.1016/j.carbpol.2011.08.078.

[11] Rbihi S, el hallani G, Bakkardouch F, Nouri A, Laallam L, liba A, et al. Influence of cellulose on the thermal conductivity of cellulose based composite thin films. Therm Sci Eng Prog 2021;21:100790. https://doi.org/10.1016/j.tsep.2020.100790.

[12] Hasanin MS, Al Kiey SA. Environmentally benign corrosion inhibitors based on cellulose niacin nano-composite for corrosion of copper in sodium chloride solutions. Int J Biol Macromol 2020;161:345–54. https://doi.org/10.1016/j.ijbiomac.2020.06.040.

[13] Watkins D, Nuruddin M, Hosur M, Tcherbi-Narteh A, Jeelani S. Extraction and characterization of lignin from different biomass resources. J Mater Res Technol 2015;4:26–32. https://doi.org/10.1016/J.JMRT.2014.10.009.

[14] Rosli NA, Wan Ishak WH, Ahmad I. Eco-friendly high-density polyethylene/amorphous cellulose composites: environmental and functional value. J Clean Prod 2021;290:125886. https://doi.org/10.1016/j.jclepro.2021.125886.

[15] Neves RM, Ornaghi HL, Zattera AJ, Amico SC. Recent studies on modified cellulose/nanocellulose epoxy composites: a systematic review. Carbohydr Polym 2021;255:117366. https://doi.org/10.1016/j.carbpol.2020.117366.

[16] Manimaran P, Saravanan SP, Sanjay MR, Siengchin S, Jawaid M, Khan A. Characterization of new cellulosic fiber: dracaena reflexa as a reinforcement for polymer composite structures. J Mater Res Technol 2019;8:1952–63. https://doi.org/10.1016/J.JMRT.2018.12.015.

[17] Jawaid M, Kian LK, Fouad H, Saba N, Alothman OY, Hashem M. Morphological, structural, and thermal analysis of three part of Conocarpus cellulosic fibres. J Mater Res Technol 2021;10:24–33. https://doi.org/10.1016/J.JMRT.2020.11.108.

[18] Ramlee NA, Jawaid M, Zainudin ES, Yamani SAK. Tensile, physical and morphological properties of oil palm empty fruit bunch/sugarcane bagasse fibre reinforced phenolic hybrid composites. J Mater Res Technol 2019;8:3466–74. https://doi.org/10.1016/J.JMRT.2019.06.016.

[19] Mylsamy B, Chinnasamy V, Palaniappan SK, Subramani SP, Gopalsamy C. Effect of surface treatment on the tribological properties of Coccinia Indica cellulosic fiber reinforced polymer composites. J Mater Res Technol 2020;9:16423–34. https://doi.org/10.1016/J.JMRT.2020.11.100.

[20] Khalid MY, Al Rashid A, Arif ZU, Ahmed W, Arshad H, Zaidi AA. Natural fiber reinforced composites: Sustainable materials for emerging applications. Results Eng. 2021;11:100263. https://doi.org/10.1016/J.RINENG.2021.100263.

[21] Khalid MY, Imran R, Arif ZU, Akram N, Arshad H, Al Rashid A, et al. Developments in chemical treatments, manufacturing techniques and potential applications of natural-fibers-based biodegradable composites. Coatings 2021;11(3). https://doi.org/10.3390/coatings11030293.

[22] Reis RS, Tienne LGP, de HS Souza D, Maria de Fátima VM, Monteiro SN. Characterization of coffee parchment and innovative steam explosion treatment to obtain microfibrillated cellulose as potential composite reinforcement. J Mater Res Technol 2020;9:9412–21. https://doi.org/10.1016/J.JMRT.2020.05.099.

[23] Karimah A, Ridho MR, Munawar SS, Adi DS, Ismadi, Damayanti R, et al. A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations. J Mater Res Technol 2021;13:2442–58. https://doi.org/10.1016/J.JMRT.2021.06.014.

[24] Khalid MY, Al Rashid A, Abbas Z, Akram N, Arif ZU, Márquez FPG. Evaluation of tensile properties of glass/sisal and glass/jute fibers reinforced hybrid composites at different stacking sequences. Polymer (Korea) 2021;45(3):390–7. https://doi.org/10.7317/pk.2021.45.3.390.

[25] Anidha S, Latha N, Muthukkumar M. Reinforcement of Aramid fiber with bagasse epoxy bio-degradable composite: investigations on mechanical properties and surface morphology. J Mater Res Technol 2019;8:3198–212. https://doi.org/10.1016/J.JMRT.2019.05.008.

[26] Khalid MY, Nasir MA, Ali A, et al. Experimental and numerical characterization of tensile property of jute/carbon fabric reinforced epoxy hybrid composites. SN Appl Sci 2020;2, 577. https://doi.org/10.1007/s42452-020-2403-2.

[27] Jaafar J, Siregar JP, Mohd Salleh S, Mohd Hamdan MH, Cionita T, Rihayat T. Important considerations in manufacturing of natural fiber composites: a review. Int J Precis Eng Manuf - Green Technol 2019;6:647–64. https://doi.org/10.1007/s40684-019-00097-2.

[28] Lotfi A, Li H, Dao DV, Prusty G. Natural fiber–reinforced composites: a review on material, manufacturing, and machinability. J Thermoplast Compos Mater 2019;34:238–84. https://doi.org/10.1177/0892705719844546.

[29] Khalid MY, Al Rashid A, Arif ZU, Akram N, Arshad H, García Márquez FP. Characterization of failure strain in fiber

reinforced composites: under on-axis and off-axis loading. Crystals 2021;11(2). https://doi.org/10.3390/cryst11020216.
[30] Faruk O, Bledzki AK, Fink HP, Sain M. Biocomposites reinforced with natural fibers: 2000-2010. Prog Polym Sci 2012;37:1552–96. https://doi.org/10.1016/j.progpolymsci.2012.04.003.
[31] Gapsari F, Purnowidodo A, Hidayatullah S, Suteja S. Characterization of Timoho Fiber as a reinforcement in green composite. J Mater Res Technol 2021;13:1305–15. https://doi.org/10.1016/J.JMRT.2021.05.049.
[32] Rajesh M, Jayakrishna K, Sultan MTH, Manikandan M, Mugeshkannan V, Shah AUM, et al. The hydroscopic effect on dynamic and thermal properties of woven jute, banana, and intra-ply hybrid natural fiber composites. J Mater Res Technol 2020;9:10305–15. https://doi.org/10.1016/J.JMRT.2020.07.033.
[33] Khalid MY, Al Rashid A, Arif ZU, Sheikh MF, Arshad H, Nasir MA. Tensile strength evaluation of glass/jute fibers reinforced composites: an experimental and numerical approach. Results Eng 2021;10:100232. https://doi.org/10.1016/j.rineng.2021.100232.
[34] Arrakhiz FZ, El Achaby M, Malha M, Bensalah MO, Fassi-Fehri O, Bouhfid R, et al. Mechanical and thermal properties of natural fibers reinforced polymer composites: doum/low density polyethylene. Mater Des 2013;43:200–5. https://doi.org/10.1016/j.matdes.2012.06.056.
[35] Khalid MY, Arif ZU, Al Rashid A, Shahid MI, Ahmed W, Tariq AF, et al. Interlaminar shear strength (ILSS) characterization of fiber metal laminates (FMLs) manufactured through VARTM process. Forces Mech 2021:100038. https://doi.org/10.1016/J.FINMEC.2021.100038.
[36] Izzati Zulkifli N, Samat N, Anuar H, Zainuddin N. Mechanical properties and failure modes of recycled polypropylene/microcrystalline cellulose composites. Mater Des 2015;69:114–23. https://doi.org/10.1016/j.matdes.2014.12.053.
[37] Khalid MY, Arif ZU, Sheikh MF, Nasir MA. Mechanical characterization of glass and jute fiber-based hybrid composites fabricated through compression molding technique. Int J Mater Form 2021. https://doi.org/10.1007/s12289-021-01624-w.
[38] Silva G, Kim S, Aguilar R, Nakamatsu J. Natural fibers as reinforcement additives for geopolymers – a review of potential eco-friendly applications to the construction industry. Sustain Mater Technol 2020;23:e00132. https://doi.org/10.1016/j.susmat.2019.e00132.
[39] Lima AVNA, Cardoso JL, Lobo CJS. Research on hybrid sisal/glass composites: a review, vol. 38; 2019. https://doi.org/10.1177/0731684419847272.
[40] Siakeng R, Jawaid M, Ariffin H, Sapuan SM, Asim M, Saba N. Natural fiber reinforced polylactic acid composites: a review. Polym Compos 2019;40:446–63. https://doi.org/10.1002/pc.24747.
[41] Ramamoorthy SK, Skrifvars M, Persson A. A review of natural fibers used in biocomposites: plant, animal and regenerated cellulose fibers. Polym Rev 2015;55:107–62. https://doi.org/10.1080/15583724.2014.971124.
[42] Hyness NRJ, Vignesh NJ, Senthamaraikannan P, Saravanakumar SS, Sanjay MR. Characterization of new natural cellulosic fiber from heteropogon contortus plant. J Nat Fibers 2018;15:146–53. https://doi.org/10.1080/15440478.2017.1321516.
[43] Sobczak L, Lang RW, Haider A. Polypropylene composites with natural fibers and wood - general mechanical property profiles. Compos Sci Technol 2012;72:550–7. https://doi.org/10.1016/j.compscitech.2011.12.013.
[44] Al-Oqla FM, Sapuan SM. Natural fiber reinforced polymer composites in industrial applications: feasibility of date palm fibers for sustainable automotive industry. J Clean Prod 2014;66:347–54. https://doi.org/10.1016/j.jclepro.2013.10.050.
[45] Sen T, Paul A. Confining concrete with sisal and jute FRP as alternatives for CFRP and GFRP. Int J Sustain Built Environ 2015;4:248–64. https://doi.org/10.1016/j.ijsbe.2015.04.001.
[46] Badie MA, Mahdi E, Hamouda AMS. An investigation into hybrid carbon/glass fiber reinforced epoxy composite automotive drive shaft. Mater Des 2011;32:1485–500. https://doi.org/10.1016/j.matdes.2010.08.042.
[47] Mahesh V, Joladarashi S, Kulkarni SM. An experimental study on adhesion, flexibility, interlaminar shear strength, and damage mechanism of jute/rubber-based flexible "green" composite. J Thermoplast Compos Mater 2019:0892705719882074. https://doi.org/10.1177/0892705719882074.
[48] Thomas P, Duolikun T, Rumjit NP, Moosavi S, Lai CW, Bin Johan MR, et al. Comprehensive review on nanocellulose: recent developments, challenges and future prospects. J Mech Behav Biomed Mater 2020;110:103884. https://doi.org/10.1016/j.jmbbm.2020.103884.
[49] Mishra RK, Sabu A, Tiwari SK. Materials chemistry and the futurist eco-friendly applications of nanocellulose: status and prospect. J Saudi Chem Soc 2018;22:949–78. https://doi.org/10.1016/j.jscs.2018.02.005.
[50] Mehanny S, Abu-El Magd EE, Ibrahim M, Farag M, Gil-San-Millan R, Navarro J, et al. Extraction and characterization of nanocellulose from three types of palm residues. J Mater Res Technol 2021;10:526–37. https://doi.org/10.1016/J.JMRT.2020.12.027.
[51] Tanpichai S, Witayakran S, Srimarut Y, Woraprayote W, Malila Y. Porosity, density and mechanical properties of the paper of steam exploded bamboo microfibers controlled by nanofibrillated cellulose. J Mater Res Technol 2019;8:3612–22. https://doi.org/10.1016/J.JMRT.2019.05.024.
[52] Faria LUS, Pacheco BJS, Oliveira GC, Silva JL. Production of cellulose nanocrystals from pineapple crown fibers through alkaline pretreatment and acid hydrolysis under different conditions. J Mater Res Technol 2020;9:12346–53. https://doi.org/10.1016/J.JMRT.2020.08.093.
[53] Abral H, Fajri N, Mahardika M, Handayani D, Sugiarti E, Kimd HJ. A simple strategy in enhancing moisture and thermal resistance and tensile properties of disintegrated bacterial cellulose nanopaper. J Mater Res Technol 2020;9:8754–65. https://doi.org/10.1016/J.JMRT.2020.06.023.
[54] Onuaguluchi O, Banthia N. Plant-based natural fibre reinforced cement composites: a review. Cement Concr Compos 2016;68:96–108. https://doi.org/10.1016/j.cemconcomp.2016.02.014.
[55] Mohammed L, Ansari MNM, Pua G, Jawaid M, Islam MS. A review on natural fiber reinforced polymer composite and its applications. Int J Polym Sci 2015;2015. https://doi.org/10.1155/2015/243947.
[56] Fagone M, Loccarini F, Ranocchiai G. Strength evaluation of jute fabric for the reinforcement of rammed earth structures. Compos B Eng 2017;113:1–13. https://doi.org/10.1016/j.compositesb.2016.12.054.
[57] Weiss CK, Isogai A, Konwarh R. Nanocellulose: from fundamentals to advanced applications. Front Chem 2020;1:392. https://doi.org/10.3389/fchem.2020.00392. WwwFrontiersinOrg.
[58] Zhang M, Matinlinna JP. E-glass fiber reinforced composites in dental applications. Silicon 2012;4:73–8. https://doi.org/10.1007/s12633-011-9075-x.
[59] Kumar R, Ul Haq MI, Raina A, Anand A. Industrial applications of natural fibre-reinforced polymer composites–challenges and opportunities. Int J Sustain Eng 2019;12:212–20. https://doi.org/10.1080/19397038.2018.1538267.

[60] Klemm D, Cranston ED, Fischer D, Gama M, Kedzior SA, Kralisch D, et al. Nanocellulose as a natural source for groundbreaking applications in materials science: Today's state. Mater Today 2018;21:720–48. https://doi.org/10.1016/j.mattod.2018.02.001.
[61] Wang D, Wang D. A critical review of cellulose-based nanomaterials for water purification in industrial processes. Cellulose 2019;26:687–701. https://doi.org/10.1007/s10570-018-2143-2.
[62] Shah N, Fehrenbach J, Ulven CA. Hybridization of hemp fiber and recycled-carbon fiber in polypropylene composites. Sustain 2019;11. https://doi.org/10.3390/su11113163.
[63] Militký J, Jabbar A. Comparative evaluation of fiber treatments on the creep behavior of jute/green epoxy composites. Compos B Eng 2015;80:361–8. https://doi.org/10.1016/j.compositesb.2015.06.014.
[64] Errokh A, Magnin A, Putaux J-L, Boufi S. Morphology of the nanocellulose produced by periodate oxidation and reductive treatment of cellulose fibers. Cellulose 2018;25:3899–911. https://doi.org/10.1007/s10570-018-1871-7.
[65] Rambabu N, Panthapulakkal S, Sain M, Dalai AK. Production of nanocellulose fibers from pinecone biomass: evaluation and optimization of chemical and mechanical treatment conditions on mechanical properties of nanocellulose films. Ind Crop Prod 2016;83:746–54. https://doi.org/10.1016/j.indcrop.2015.11.083.
[66] Martelli-Tosi M, Masson MM, Silva NC, Esposto BS, Barros TT, Assis OBG, et al. Soybean straw nanocellulose produced by enzymatic or acid treatment as a reinforcing filler in soy protein isolate films. Carbohydr Polym 2018;198:61–8. https://doi.org/10.1016/j.carbpol.2018.06.053.
[67] Asrofi M, Abral H, Kasim A, Pratoto A, Mahardika M, Park J-W, et al. Isolation of nanocellulose from water hyacinth fiber (WHF) produced via digester-sonication and its characterization. Fibers Polym 2018;19:1618–25. https://doi.org/10.1007/s12221-018-7953-1.
[68] Mahardika M, Abral H, Kasim A, Arief S, Asrofi M. Production of nanocellulose from pineapple leaf fibers via high-shear homogenization and ultrasonication. Fibers 2018;6. https://doi.org/10.3390/fib6020028.
[69] Nascimento P, Marim R, Carvalho G, Mali S. Nanocellulose produced from rice hulls and its effect on the properties of biodegradable starch films. Mater Res 2016;19:167–74. https://doi.org/10.1590/1980-5373-MR-2015-0423.
[70] Deepa B, Abraham E, Cordeiro N, Mozetic M, Mathew AP, Oksman K, et al. Utilization of various lignocellulosic biomass for the production of nanocellulose: a comparative study. Cellulose 2015;22:1075–90. https://doi.org/10.1007/s10570-015-0554-x.
[71] Lamaming J, Hashim R, Leh CP, Sulaiman O, Sugimoto T, Nasir M. Isolation and characterization of cellulose nanocrystals from parenchyma and vascular bundle of oil palm trunk (Elaeis guineensis). Carbohydr Polym 2015;134:534–40. https://doi.org/10.1016/j.carbpol.2015.08.017.
[72] Lu Q, Lin W, Tang L, Wang S, Chen X, Huang B. A mechanochemical approach to manufacturing bamboo cellulose nanocrystals. J Mater Sci 2015;50:611–9. https://doi.org/10.1007/s10853-014-8620-6.
[73] Danial WH, Abdul Majid Z, Mohd Muhid MN, Triwahyono S, Bakar MB, Ramli Z. The reuse of wastepaper for the extraction of cellulose nanocrystals. Carbohydr Polym 2015;118:165–9. https://doi.org/10.1016/j.carbpol.2014.10.072.
[74] Tibolla H, Pelissari FM, Menegalli FC. Cellulose nanofibers produced from banana peel by chemical and enzymatic treatment. LWT–Food Sci Technol 2014;59:1311–8. https://doi.org/10.1016/j.lwt.2014.04.011.
[75] Abraham E, Deepa B, Pothen LA, Cintil J, Thomas S, John MJ, et al. Environmental friendly method for the extraction of coir fibre and isolation of nanofibre. Carbohydr Polym 2013;92:1477–83. https://doi.org/10.1016/j.carbpol.2012.10.056.
[76] Thomas MG, Abraham E, Jyotishkumar P, Maria HJ, Pothen LA, Thomas S. Nanocelluloses from jute fibers and their nanocomposites with natural rubber: preparation and characterization. Int J Biol Macromol 2015;81:768–77. https://doi.org/10.1016/j.ijbiomac.2015.08.053.
[77] Shahabi-Ghahafarrokhi I, Khodaiyan F, Mousavi M, Yousefi H. Preparation and characterization of nanocellulose from beer industrial residues using acid hydrolysis/ultrasound. Fibers Polym 2015;16:529–36. https://doi.org/10.1007/s12221-015-0529-4.
[78] Hassan SH, Velayutham TS, Chen YW, Lee HV. TEMPO-oxidized nanocellulose films derived from coconut residues: physicochemical, mechanical and electrical properties. Int J Biol Macromol 2021;180:392–402. https://doi.org/10.1016/j.ijbiomac.2021.03.066.
[79] Wu C, Egawa S, Kanno T, Kurita H, Wang Z, Iida E, et al. Nanocellulose reinforced silkworm silk fibers for application to biodegradable polymers. Mater Des 2021;202:109537. https://doi.org/10.1016/j.matdes.2021.109537.
[80] Csiszár E, Nagy S. A comparative study on cellulose nanocrystals extracted from bleached cotton and flax and used for casting films with glycerol and sorbitol plasticisers. Carbohydr Polym 2017;174:740–9. https://doi.org/10.1016/J.CARBPOL.2017.06.103.
[81] Voisin H, Bergström L, Liu P, Mathew AP, Luong JHT, Kumar Vashist S. Nanocellulose-based materials for water purification. Nanomaterials 2017. https://doi.org/10.3390/nano7030057.
[82] Macedo MJP, Silva GS, Feitor MC, Costa THC, Ito EN, Melo JDD. Surface modification of kapok fibers by cold plasma surface treatment. J Mater Res Technol 2020;9:2467–76. https://doi.org/10.1016/J.JMRT.2019.12.077.
[83] Gallego R, Piras CC, Rutgeerts LAJ, Fernandez-Prieto S, De Borggraeve WM, Franco JM, et al. Green approach for the activation and functionalization of jute fibers through ball milling. Cellulose 2020;27:643–56. https://doi.org/10.1007/s10570-019-02831-0.
[84] Vijay R, Vinod A, Lenin Singaravelu D, Sanjay MR, Siengchin S. Characterization of chemical treated and untreated natural fibers from Pennisetum orientale grass- A potential reinforcement for lightweight polymeric applications. Int J Light Mater Manuf 2021;4:43–9. https://doi.org/10.1016/J.IJLMM.2020.06.008.
[85] Xie Y, Hill CAS, Xiao Z, Militz H, Mai C. Silane coupling agents used for natural fiber/polymer composites: a review. Compos Part A Appl Sci Manuf 2010;41:806–19. https://doi.org/10.1016/j.compositesa.2010.03.005.
[86] Reddy BM, Mohana Reddy YV, Mohan Reddy BC, Reddy RM. Mechanical, morphological, and thermogravimetric analysis of alkali-treated Cordia-Dichotoma natural fiber composites. J Nat Fibers 2020;17:759–68. https://doi.org/10.1080/15440478.2018.1534183.
[87] Shalwan A, Yousif BF. In state of art: mechanical and tribological behaviour of polymeric composites based on natural fibres. Mater Des 2013;48:14–24. https://doi.org/10.1016/j.matdes.2012.07.014.
[88] Jahan F, Soni M. Effects of chemical treatment on mechanical properties of various natural fiber reinforced composite: a review. Mater Today Proc 2021. https://doi.org/10.1016/J.MATPR.2021.04.175.

[89] Senthilraja R, Sarala R, Godwin Antony A, Seshadhri. Effect of acetylation technique on mechanical behavior and durability of palm fibre vinyl-ester composites. Mater Today Proc 2020;21:634–7. https://doi.org/10.1016/j.matpr.2019.06.729.

[90] Loganathan TM, Sultan MTH, Ahsan Q, Jawaid M, Naveen J, Md Shah AU, et al. Characterization of alkali treated new cellulosic fibre from Cyrtostachys renda. J Mater Res Technol 2020;9:3537–46. https://doi.org/10.1016/J.JMRT.2020.01.091.

[91] Najeeb MI, Sultan MTH, Andou Y, Shah AUM, Eksiler K, Jawaid M, et al. Characterization of silane treated Malaysian Yankee Pineapple AC6 leaf fiber (PALF) towards industrial applications. J Mater Res Technol 2020;9:3128–39. https://doi.org/10.1016/J.JMRT.2020.01.058.

[92] Izwan SM, Sapuan SM, Zuhri MYM, Mohamed AR. Effects of benzoyl treatment on NaOH treated sugar palm fiber: tensile, thermal, and morphological properties. J Mater Res Technol 2020;9:5805–14. https://doi.org/10.1016/J.JMRT.2020.03.105.

[93] Barczewski M, Matykiewicz D, Szostak M. The effect of two-step surface treatment by hydrogen peroxide and silanization of flax/cotton fabrics on epoxy-based laminates thermomechanical properties and structure. J Mater Res Technol 2020;9:13813–24. https://doi.org/10.1016/J.JMRT.2020.09.120.

[94] Imoisili PE, Jen T-C. Mechanical and water absorption behaviour of potassium permanganate (KMnO4) treated plantain (Musa Paradisiacal) fibre/epoxy bio-composites. J Mater Res Technol 2020;9:8705–13. https://doi.org/10.1016/J.JMRT.2020.05.121.

[95] Liu Y, Xie J, Wu N, Wang L, Ma Y, Tong J. Influence of silane treatment on the mechanical, tribological and morphological properties of corn stalk fiber reinforced polymer composites. Tribol Int 2019;131:398–405. https://doi.org/10.1016/j.triboint.2018.11.004.

[96] Madhu P, Sanjay MR, Senthamaraikannan P, Pradeep S, Saravanakumar SS, Yogesha B. A review on synthesis and characterization of commercially available natural fibers: Part-I. J Nat Fibers 2019;16:1132–44. https://doi.org/10.1080/15440478.2018.1453433.

[97] Shrivastava R, Christy A, Telang A, Rana RS. Effect of chemical treatment and curing parameters on mechanical properties of natural fiber reinforced polymer matrix composites-A review. J Eng Res Appl 2015;5:70–5.

[98] Nurazzi NM, Harussani MM, Aisyah HA, Ilyas RA, Norrrahim MNF, Khalina A, et al. Treatments of natural fiber as reinforcement in polymer composites-a short review. 2020. https://doi.org/10.1088/2631-6331/abff36.

[99] Georgiopoulos P, Kontou E, Georgousis G. Effect of silane treatment loading on the flexural properties of PLA/flax unidirectional composites. Compos Commun 2018;10:6–10. https://doi.org/10.1016/j.coco.2018.05.002.

[100] Kabir MM, Wang H, Lau KT, Cardona F. Chemical treatments on plant-based natural fibre reinforced polymer composites: an overview. Compos B Eng 2012;43:2883–92. https://doi.org/10.1016/j.compositesb.2012.04.053.

[101] Jayamani E, Hamdan S, Rahman MR, Bakri MK Bin. Comparative study of dielectric properties of hybrid natural fiber composites. Procedia Eng 2014;97:536–44. https://doi.org/10.1016/j.proeng.2014.12.280.

[102] Osong SH, Norgren S, Engstrand P. Processing of wood-based microfibrillated cellulose and nanofibrillated cellulose, and applications relating to papermaking: a review. Cellulose 2016. https://doi.org/10.1007/s10570-015-0798-5.

[103] Sanaeishoar H, Sabbaghan M, Argyropoulos DS. Ultrasound assisted polyacrylamide grafting on nano-fibrillated cellulose. Carbohydr Polym 2018;181:1071–7. https://doi.org/10.1016/j.carbpol.2017.11.042.

[104] Missoum K, Belgacem MN, Bras J. Nanofibrillated cellulose surface modification: a review. Materials (Basel) 2013;6:1745–66. https://doi.org/10.3390/ma6051745.

[105] Naderi A. Nanofibrillated cellulose: properties reinvestigated. Cellulose 2016;24. https://doi.org/10.1007/s10570-017-1258-1.

[106] Abdul Khalil HPS, Davoudpour Y, Islam MN, Mustapha A, Sudesh K, Dungani R, et al. Production and modification of nanofibrillated cellulose using various mechanical processes: a review. Carbohydr Polym 2014;99:649–65. https://doi.org/10.1016/j.carbpol.2013.08.069.

[107] Nechyporchuk O, Belgacem MN, Bras J. Production of cellulose nanofibrils: a review of recent advances. Ind Crop Prod 2016;93:2–25. https://doi.org/10.1016/j.indcrop.2016.02.016.

[108] Kamasamudram KS, Ashraf W, Landis EN, Khan RI. Effects of ligno– and delignified– cellulose nanofibrils on the performance of cement-based materials. J Mater Res Technol 2021;13:321–35. https://doi.org/10.1016/J.JMRT.2021.04.090.

[109] Kekäläinen K, Liimatainen H, Illikainen M, Maloney TC, Niinimäki J. The role of hornification in the disintegration behaviour of TEMPO-oxidized bleached hardwood fibres in a high-shear homogenizer. Cellulose 2014. https://doi.org/10.1007/s10570-014-0210-x.

[110] Jiang F, Hsieh Y Lo. Amphiphilic superabsorbent cellulose nanofibril aerogels. J Mater Chem 2014;2:6337–42. https://doi.org/10.1039/c4ta00743c.

[111] Jimenez LML. Synthesis of carbon nano structures by plasma discharge. 2007.

[112] Xu Y, Li S, Yue X, Lu W. Review of Silver nanoparticles (AgNPs)-cellulose antibacterial composites. BioResources 2018;13:2150–70. https://doi.org/10.15376/biores.13.1.Xu.

[113] Ferrero F, Migliavacca G, Periolatto M. UV treatments on cotton fibers. Cott Res 2016:235–56.

[114] Tabak C, Keskin S, Akbasak T, Ozkoc G. Polypropylene/spray dried and silane-treated nanofibrillated cellulose composites. Polym Eng Sci 2020;60:352–61.

[115] Niamsap T, Lam NT, Sukyai P. Production of hydroxyapatite-bacterial nanocellulose scaffold with assist of cellulose nanocrystals. Carbohydr Polym 2019;205:159–66. https://doi.org/10.1016/j.carbpol.2018.10.034.

[116] Sakovich GV, Skiba EA, Budaeva VV, Gladysheva EK, Aleshina LA. Original Russian text ©. Dokl Biochem Biophys 2017;477:109–12. https://doi.org/10.1134/S1607672917060047.

[117] Kuo CH, Chen JH, Liou BK, Lee CK. Utilization of acetate buffer to improve bacterial cellulose production by Gluconacetobacter xylinus. Food Hydrocoll 2016;53:98–103. https://doi.org/10.1016/j.foodhyd.2014.12.034.

[118] Abral H, Chairani MK, Rizki MD, Mahardika M, Handayani D, Sugiarti E, et al. Characterization of compressed bacterial cellulose nanopaper film after exposure to dry and humid conditions. J Mater Res Technol 2021;11:896–904. https://doi.org/10.1016/J.JMRT.2021.01.057.

[119] Huang C, Guo HJ, Xiong L, Wang B, Shi SL, Chen XF, et al. Using wastewater after lipid fermentation as substrate for bacterial cellulose production by Gluconacetobacter xylinus. Carbohydr Polym 2016;136:198–202. https://doi.org/10.1016/j.carbpol.2015.09.043.

[120] Abol-Fotouh D, Hassan MA, Shokry H, Roig A, Azab MS, El-Hady Abd, et al. Bacterial nanocellulose from agro-industrial wastes: low-cost and enhanced production by Komagataeibacter saccharivorans MD1. Sci Rep 2020. https://doi.org/10.1038/s41598-020-60315-9.

[121] Molina-Ramírez C, Álvarez J, Zuluaga R, Castro C, Gañán P. A novel approach using conventional methodologies to

scale up BNC production using Komagataeibacter medellinensis and rotten banana waste as alternative. Processes 2020. https://doi.org/10.3390/pr8111469.

[122] Sharma C, Bhardwaj NK, Pathak P. Static intermittent fed-batch production of bacterial nanocellulose from black tea and its modification using chitosan to develop antibacterial green packaging material. J Clean Prod 2021;279:123608. https://doi.org/10.1016/j.jclepro.2020.123608.

[123] Jeremic S, Djokic L, Ajdačić V, Božinović N, Pavlovic V, Manojlović DD, et al. Production of bacterial nanocellulose (BNC) and its application as a solid support in transition metal catalysed cross-coupling reactions. Int J Biol Macromol 2019;129:351–60. https://doi.org/10.1016/j.ijbiomac.2019.01.154.

[124] Rodrigues AC, Fontão AI, Coelho A, Leal M, Soares da Silva FAG, Wan Y, et al. Response surface statistical optimization of bacterial nanocellulose fermentation in static culture using a low-cost medium. Nat Biotechnol 2019;49:19–27. https://doi.org/10.1016/j.nbt.2018.12.002.

[125] Sharma C, Bhardwaj NK. Bacterial nanocellulose: present status, biomedical applications and future perspectives. Mater Sci Eng C 2019;104:109963. https://doi.org/10.1016/j.msec.2019.109963.

[126] Lin N, Dufresne A. Nanocellulose in biomedicine: current status and future prospect. Eur Polym J 2014;59:302–25. https://doi.org/10.1016/j.eurpolymj.2014.07.025.

[127] Dehnad D, Emam-Djomeh Z, Mirzaei H, Jafari SM, Dadashi S. Optimization of physical and mechanical properties for chitosan- nanocellulose biocomposites. Carbohydr Polym 2014;105:222–8. https://doi.org/10.1016/j.carbpol.2014.01.094.

[128] Walther A, Lossada F, Benselfelt T, Kriechbaum K, Berglund L, Ikkala O, et al. Best practice for reporting wet mechanical properties of nanocellulose-based materials. Biomacromolecules 2020;21:2536–40. https://doi.org/10.1021/acs.biomac.0c00330.

[129] McKee JR, Hietala S, Seitsonen J, Laine J, Kontturi E, Ikkala O. Thermoresponsive nanocellulose hydrogels with tunable mechanical properties. ACS Macro Lett 2014;3:266–70. https://doi.org/10.1021/mz400596g.

[130] Wang Z, Kang K, Wu J, Hu Q, Harper DP, Du G, et al. Comparative effects of electrospinning ways for fabricating green, sustainable, flexible, porous, nanofibrous cellulose/chitosan carbon mats as anode materials for lithium-ion batteries. J Mater Res Technol 2021;11:50–61. https://doi.org/10.1016/J.JMRT.2021.01.009.

[131] Thomas B, Raj MC, Joy J, Moores A, Drisko GL, Sanchez C. Nanocellulose, a versatile green platform: from biosources to materials and their applications. Chem Rev 2018;118:11575–625. https://doi.org/10.1021/acs.chemrev.7b00627.

[132] Ghasemi S, Behrooz R, Ghasemi I, Yassar RS, Long F. Development of nanocellulose-reinforced PLA nanocomposite by using maleated PLA (PLA-g-MA). J Thermoplast Compos Mater 2018;31:1090–101.

[133] Carrillo CA, Nypelö T, Rojas OJ. Double emulsions for the compatibilization of hydrophilic nanocellulose with non-polar polymers and validation in the synthesis of composite fibers. Soft Matter 2016;12:2721–8.

[134] Wu Y, Xia C, Cai L, Garcia AC, Shi SQ. Development of natural fiber-reinforced composite with comparable mechanical properties and reduced energy consumption and environmental impacts for replacing automotive glass-fiber sheet molding compound. J Clean Prod 2018;184:92–100.

[135] Morelli CL, Belgacem MN, Branciforti MC, Bretas RES, Crisci A, Bras J. Supramolecular aromatic interactions to enhance biodegradable film properties through incorporation of functionalized cellulose nanocrystals. Compos Part A Appl Sci Manuf 2016;83:80–8.

[136] Tan C, Peng J, Lin W, Xing Y, Xu K, Wu J, et al. Role of surface modification and mechanical orientation on property enhancement of cellulose nanocrystals/polymer nanocomposites. Eur Polym J 2015;62:186–97.

[137] Spinella S, Lo Re G, Liu B, Dorgan J, Habibi Y, Leclere P, et al. Polylactide/cellulose nanocrystal nanocomposites: efficient routes for nanofiber modification and effects of nanofiber chemistry on PLA reinforcement. Polymer (Guildf) 2015;65:9–17.

[138] Karim Z, Claudpierre S, Grahn M, Oksman K, Mathew AP. Nanocellulose based functional membranes for water cleaning: tailoring of mechanical properties, porosity and metal ion capture. J Membr Sci 2016;514:418–28. https://doi.org/10.1016/j.memsci.2016.05.018.

[139] Rojo E, Peresin MS, Sampson WW, Hoeger IC, Vartiainen J, Laine J, et al. Comprehensive elucidation of the effect of residual lignin on the physical, barrier, mechanical and surface properties of nanocellulose films. Green Chem 2015;17:1853. https://doi.org/10.1039/c4gc02398f.

[140] Ambone T, Torris A, Shanmuganathan K. Enhancing the mechanical properties of 3D printed polylactic acid using nanocellulose. Polym Eng Sci 2020;60:1842–55.

[141] Ifuku S, Yano H. Effect of a silane coupling agent on the mechanical properties of a microfibrillated cellulose composite. Int J Biol Macromol 2015;74:428–32. https://doi.org/10.1016/j.ijbiomac.2014.12.029.

[142] Awal A, Rana M, Sain M. Thermorheological and mechanical properties of cellulose reinforced PLA bio-composites. Mech Mater 2015;80:87–95. https://doi.org/10.1016/j.mechmat.2014.09.009.

[143] Qi H, Schulz B, Vad T, Liu J, Mäder E, Seide G, et al. Novel carbon nanotube/cellulose composite fibers as multifunctional materials. ACS Appl Mater Interfaces 2015;7:22404–12. https://doi.org/10.1021/acsami.5b06229.

[144] Piltonen P, Hildebrandt NC, Westerlind B, Valkama JP, Tervahartiala T, Illikainen M. Green and efficient method for preparing all-cellulose composites with NaOH/urea solvent. Compos Sci Technol 2016;135:153–8. https://doi.org/10.1016/j.compscitech.2016.09.022.

[145] Saba N, Safwan A, Sanyang ML, Mohammad F, Pervaiz M, Jawaid M, et al. Thermal and dynamic mechanical properties of cellulose nanofibers reinforced epoxy composites. Int J Biol Macromol 2017;102:822–8. https://doi.org/10.1016/j.ijbiomac.2017.04.074.

[146] Zhang S, Zhang F, Pan Y, Jin L, Liu B, Mao Y, et al. Multiwall-carbon-nanotube/cellulose composite fibers with enhanced mechanical and electrical properties by cellulose grafting. 2018. https://doi.org/10.1039/c7ra11304h.

[147] Korhonen O, Budtova T. All-cellulose composite aerogels and cryogels. Compos Part A Appl Sci Manuf 2020;137:106027. https://doi.org/10.1016/j.compositesa.2020.106027.

[148] Aarstad O, Heggset EB, Pedersen IS, Bjørnøy SH, Syverud K, Strand BL. Mechanical properties of composite hydrogels of alginate and cellulose nanofibrils. Polym 2017;9. https://doi.org/10.3390/polym9080378.

[149] Hassan MM, Tucker N, Le Guen MJ. Thermal, mechanical and viscoelastic properties of citric acid-crosslinked starch/cellulose composite foams. Carbohydr Polym 2020;230:115675. https://doi.org/10.1016/j.carbpol.2019.115675.

[150] Liu H, Liu C, Peng S, Pan B, Lu C. Effect of polyethyleneimine modified graphene on the mechanical and water vapor barrier properties of methyl cellulose composite films. Carbohydr Polym 2018;182:52–60. https://doi.org/10.1016/j.carbpol.2017.11.008.

[151] Qiu C, Zhu K, Yang W, Wang Y, Zhang L, Chen F, et al. Super strong all-cellulose composite filaments by combination of inducing nanofiber formation and adding nanofibrillated cellulose. Biomacromolecules 2018;19:4386–95. https://doi.org/10.1021/acs.biomac.8b01262.
[152] Mulinari DR, Voorwald HJC, Cioffi MOH, da Silva MLCP. Cellulose fiber-reinforced high-density polyethylene composites—mechanical and thermal properties. J Compos Mater 2017;51:1807–15. https://doi.org/10.1177/0021998316665241.
[153] Chen Y, Pötschke P, Pionteck J, Voit B, Qi H. Smart cellulose/graphene composites fabricated by: in situ chemical reduction of graphene oxide for multiple sensing applications. J Mater Chem 2018;6:7777–85. https://doi.org/10.1039/c8ta00618k.
[154] Gupta A, Simmons W, Schueneman GT, Hylton D, Mintz EA. Rheological and thermo-mechanical properties of poly(lactic acid)/lignin-coated cellulose nanocrystal composites. ACS Sustain Chem Eng 2017;5:1711–20. https://doi.org/10.1021/acssuschemeng.6b02458.
[155] Babaee M, Jonoobi M, Hamzeh Y, Ashori A. Biodegradability and mechanical properties of reinforced starch nanocomposites using cellulose nanofibers. Carbohydr Polym 2015;132:1–8. https://doi.org/10.1016/j.carbpol.2015.06.043.
[156] Cai J, Chen J, Zhang Q, Lei M, He J, Xiao A, et al. Well-aligned cellulose nanofiber-reinforced polyvinyl alcohol composite film: mechanical and optical properties. Carbohydr Polym 2016;140:238–45. https://doi.org/10.1016/j.carbpol.2015.12.039.
[157] Cazón P, Vázquez M, Velazquez G. Cellulose-glycerol-polyvinyl alcohol composite films for food packaging: evaluation of water adsorption, mechanical properties, light-barrier properties and transparency. Carbohydr Polym 2018;195:432–43. https://doi.org/10.1016/j.carbpol.2018.04.120.
[158] Rehman MM, Zeeshan M, Shaker K, Nawab Y. Effect of micro-crystalline cellulose particles on mechanical properties of alkaline treated jute fabric reinforced green epoxy composite. Cellulose 2019;26:9057–69. https://doi.org/10.1007/s10570-019-02679-4.
[159] Wang X, Wang S, Liu W, Wang S, Zhang L, Sang R, et al. Facile fabrication of cellulose composite films with excellent UV resistance and antibacterial activity. Carbohydr Polym 2019;225:115213. https://doi.org/10.1016/j.carbpol.2019.115213.
[160] Kassab Z, Aziz F, Hannache H, Ben Youcef H, El Achaby M. Improved mechanical properties of k-carrageenan-based nanocomposite films reinforced with cellulose nanocrystals. Int J Biol Macromol 2019;123:1248–56. https://doi.org/10.1016/j.ijbiomac.2018.12.030.
[161] Chen Y, Hou X, Kang R, Liang Y, Guo L, Dai W, et al. Highly flexible biodegradable cellulose nanofiber/graphene heat-spreader films with improved mechanical properties and enhanced thermal conductivity. J Mater Chem C 2018;6:12739–45. https://doi.org/10.1039/c8tc04859b.
[162] Maslinda AB, Abdul Majid MS, Ridzuan MJM, Afendi M, Gibson AG. Effect of water absorption on the mechanical properties of hybrid interwoven cellulosic-cellulosic fibre reinforced epoxy composites. Compos Struct 2017;167:227–37. https://doi.org/10.1016/j.compstruct.2017.02.023.
[163] Wang W, Liang T, Bai H, Dong W, Liu X. All cellulose composites based on cellulose diacetate and nanofibrillated cellulose prepared by alkali treatment. Carbohydr Polym 2018;179:297–304. https://doi.org/10.1016/j.carbpol.2017.09.098.
[164] Nair SS, Zhu JY, Deng Y, Ragauskas AJ. High performance green barriers based on nanocellulose. 2014. https://doi.org/10.1186/s40508-014-0023-0.
[165] Reis RS, Souza D de HS, Marques M de FV, da Luz FS, Monteiro SN. Novel bionanocomposite of polycaprolactone reinforced with steam-exploded microfibrillated cellulose modified with ZnO. J Mater Res Technol 2021;13:1324–35. https://doi.org/10.1016/J.JMRT.2021.05.043.
[166] Fortunati E, Peltzer M, Armentano I, Jiménez A, Kenny JM. Combined effects of cellulose nanocrystals and silver nanoparticles on the barrier and migration properties of PLA nano-biocomposites. J Food Eng 2013;118:117–24. https://doi.org/10.1016/j.jfoodeng.2013.03.025.
[167] Poonguzhali R, Basha SK, Kumari VS. Synthesis and characterization of chitosan-PVP-nanocellulose composites for in-vitro wound dressing application. Int J Biol Macromol 2017;105:111–20. https://doi.org/10.1016/J.IJBIOMAC.2017.07.006.
[168] Ferrer A, Pal L, Hubbe M. Nanocellulose in packaging: advances in barrier layer technologies. Ind Crop Prod 2017;95:574–82. https://doi.org/10.1016/J.INDCROP.2016.11.012.
[169] Honorato C, Kumar V, Liu J, Koivula H, Xu C, Toivakka M. Transparent nanocellulose-pigment composite films. J Mater Sci 2015;50. https://doi.org/10.1007/s10853-015-9291-7.
[170] Ha D, Fang Z, Zhitenev NB. Paper in electronic and optoelectronic devices. Adv Electron Mater 2018;4:1700593. https://doi.org/10.1002/aelm.201700593.
[171] Zhang Y, Zhang L, Cui K, Ge S, Cheng X, Yan M, et al. Flexible electronics based on micro/nanostructured paper. Adv Mater 2018;30:1801588. https://doi.org/10.1002/adma.201801588.
[172] Someya T, Bao Z, Malliaras GG. The rise of plastic bioelectronics. Nature 2016;540:379–85. https://doi.org/10.1038/nature21004.
[173] Okahisa Y, Yoshida A, Miyaguchi S, Yano H. Optically transparent wood–cellulose nanocomposite as a base substrate for flexible organic light-emitting diode displays. Compos Sci Technol 2009;69:1958–61. https://doi.org/10.1016/J.COMPSCITECH.2009.04.017.
[174] Zhu H, Xiao Z, Liu D, Li Y, Weadock NJ, Fang Z, et al. Biodegradable transparent substrates for flexible organic-light-emitting diodes. Energy Environ Sci 2013;6:2105–11.
[175] Purandare S, Gomez EF, Steckl AJ. High brightness phosphorescent organic light emitting diodes on transparent and flexible cellulose films. Nanotechnology 2014;25:94012. https://doi.org/10.1088/0957-4484/25/9/094012.
[176] Ummartyotin S, Juntaro J, Sain M, Manuspiya H. Development of transparent bacterial cellulose nanocomposite film as substrate for flexible organic light emitting diode (OLED) display. Ind Crop Prod 2012;35:92–7. https://doi.org/10.1016/j.indcrop.2011.06.025.
[177] Furlan DM, Morgado DL, Oliveira AJAD, Faceto ÂD, Moraes DAD, Varanda LC, et al. Sisal cellulose and magnetite nanoparticles: formation and properties of magnetic hybrid films. J Mater Res Technol 2019;8:2170–9. https://doi.org/10.1016/J.JMRT.2019.02.005.
[178] Erbas Kiziltas E, Kiziltas A, Bollin SC, Gardner DJ. Preparation and characterization of transparent PMMA-cellulose-based nanocomposites. Carbohydr Polym 2015;127:381–9. https://doi.org/10.1016/j.carbpol.2015.03.029.
[179] Palem RR, Ramesh S, Yadav HM, Kim JH, Sivasamy A, Kim HS, et al. Nanostructured Fe2O3@nitrogen-doped multiwalled nanotube/cellulose nanocrystal composite material electrodes for high-performance supercapacitor applications. J Mater Res Technol 2020;9:7615–27. https://doi.org/10.1016/J.JMRT.2020.05.058.
[180] Fang Z, Hou G, Chen C, Hu L. Nanocellulose-based films and their emerging applications. Curr Opin Solid State Mater Sci

2019;23:100764. https://doi.org/10.1016/j.cossms.2019.07.003.
[181] Daniele MA, Knight AJ, Roberts SA, Radom K, Erickson JS. Sweet substrate: a polysaccharide nanocomposite for conformal electronic decals. Adv Mater 2015;27:1600–6. https://doi.org/10.1002/adma.201404445.
[182] Syafiq R, Sapuan SM, Zuhri MRM. Antimicrobial activity, physical, mechanical and barrier properties of sugar palm based nanocellulose/starch biocomposite films incorporated with cinnamon essential oil. J Mater Res Technol 2021;11:144–57. https://doi.org/10.1016/J.JMRT.2020.12.091.
[183] Schyrr B, Pasche S, Voirin G, Weder C, Simon YC, Foster EJ. Biosensors based on porous cellulose nanocrystal-poly(vinyl alcohol) scaffolds. ACS Appl Mater Interfaces 2014;6:12674–83. https://doi.org/10.1021/am502670u.
[184] Park J, Seo J-H, Yeom S-W, Yao C, Yang VW, Cai Z, et al. Flexible and transparent organic phototransistors on biodegradable cellulose nanofibrillated fiber substrates. Adv Opt Mater 2018;6:1701140. https://doi.org/10.1002/adom.201701140.
[185] Abouzeid RE, Khiari R, El-Wakil N, Dufresne A. Current state and new trends in the use of cellulose nanomaterials for wastewater treatment. Biomacromolecules 2018;20:573–97.
[186] Yu H-Y, Zhang D-Z, Lu F-F, Yao J. New approach for single-step extraction of carboxylated cellulose nanocrystals for their use as adsorbents and flocculants. ACS Sustain Chem Eng 2016;4:2632–43. https://doi.org/10.1021/acssuschemeng.6b00126.
[187] Cao X, Huang M, Ding B, Yu J, Sun G. Robust polyacrylonitrile nanofibrous membrane reinforced with jute cellulose nanowhiskers for water purification. Desalination 2013;316:120–6. https://doi.org/10.1016/j.desal.2013.01.031.
[188] Kuang Y, Chen C, He S, Hitz EM, Wang Y, Gan W, et al. A high-performance self-regenerating solar evaporator for continuous water desalination. Adv Mater 2019;31:1900498. https://doi.org/10.1002/adma.201900498.
[189] Chen C, Kuang Y, Hu L. Challenges and opportunities for solar evaporation. Joule 2019;3:683–718. https://doi.org/10.1016/j.joule.2018.12.023.
[190] Metreveli G, Wågberg L, Emmoth E, Belák S, Strømme M, Mihranyan A. A size-exclusion nanocellulose filter paper for virus removal. Adv Healthc Mater 2014;3:1546–50. https://doi.org/10.1002/adhm.201300641.
[191] Xu T, Jiang Q, Ghim D, Liu K-K, Sun H, Derami HG, et al. Catalytically active bacterial nanocellulose-based ultrafiltration membrane. Small 2018;14:1704006. https://doi.org/10.1002/smll.201704006.
[192] Fonseca DFS, Vilela C, Pinto RJB, Bastos V, Oliveira H, Catarino J, et al. Bacterial nanocellulose-hyaluronic acid microneedle patches for skin applications: in vitro and in vivo evaluation. Mater Sci Eng C 2021;118:111350. https://doi.org/10.1016/j.msec.2020.111350.
[193] Alkhatib Y, Blume G, Thamm J, Steiniger F, Kralisch D, Fischer D. Overcoming the hydrophilicity of bacterial nanocellulose: incorporation of the lipophilic coenzyme Q10 using lipid nanocarriers for dermal applications. Eur J Pharm Biopharm 2021;158:106–12. https://doi.org/10.1016/j.ejpb.2020.10.021.
[194] Wei Z, Pan P, Hong FF, Cao Z, Ji Y, Chen L. A novel approach for efficient fabrication of chitosan nanoparticles-embedded bacterial nanocellulose conduits. Carbohydr Polym 2021;264:118002. https://doi.org/10.1016/j.carbpol.2021.118002.
[195] Anton-Sales I, Roig-Sanchez S, Traeger K, Weis C, Laromaine A, Turon P, et al. In vivo soft tissue reinforcement with bacterial nanocellulose. 2021. https://doi.org/10.1039/d1bm00025j.
[196] Müller A, Ni Z, Hessler N, Wesarg F, Müller FA, Kralisch D, et al. The biopolymer bacterial nanocellulose as drug delivery system: investigation of drug loading and release using the model protein albumin. J Pharm Sci 2013;102:579–92. https://doi.org/10.1002/jps.23385.
[197] Moritz S, Wiegand C, Wesarg F, Hessler N, Müller FA, Kralisch D, et al. Active wound dressings based on bacterial nanocellulose as drug delivery system for octenidine. Int J Pharm 2014;471:45–55. https://doi.org/10.1016/j.ijpharm.2014.04.062.
[198] Silva NHCS, Rodrigues AF, Almeida IF, Costa PC, Rosado C, Neto CP, et al. Bacterial cellulose membranes as transdermal delivery systems for diclofenac: in vitro dissolution and permeation studies. Carbohydr Polym 2014;106:264–9. https://doi.org/10.1016/j.carbpol.2014.02.014.
[199] Widiyanti P, Amali MA, Aminatun. Poly(ethylene glycol) dimethacrylate – nanofibrillated cellulose bionanocomposites as injectable hydrogel for therapy of herniated nucleus pulposus patients. J Mater Res Technol 2020;9:12716–22. https://doi.org/10.1016/J.JMRT.2020.08.091.
[200] Jia B, Li Y, Yang B, Xiao D, Zhang S, Varada Rajulu A, et al. Effect of microcrystal cellulose and cellulose whisker on biocompatibility of cellulose-based electrospun scaffolds. Cellulose 2013. https://doi.org/10.1007/s10570-013-9952-0.
[201] Ahmed MK, Menazea AA, Mansour SF, Al-Wafi R. Differentiation between cellulose acetate and polyvinyl alcohol nanofibrous scaffolds containing magnetite nanoparticles/graphene oxide via pulsed laser ablation technique for tissue engineering applications. J Mater Res Technol 2020;9:11629–40. https://doi.org/10.1016/J.JMRT.2020.08.041.
[202] Apelgren P, Karabulut E, Amoroso M, Mantas A, Martínez Ávila H, Kölby L, et al. In vivo human cartilage formation in three-dimensional bioprinted constructs with a novel bacterial nanocellulose bioink. ACS Biomater Sci Eng 2019;5:2482–90. https://doi.org/10.1021/acsbiomaterials.9b00157.
[203] Athukoralalage SS, Balu R, Dutta NK, Roy Choudhury N. 3D bioprinted nanocellulose-based hydrogels for tissue engineering applications: a brief review. Polym 2019;11. https://doi.org/10.3390/polym11050898.
[204] Hu G, Chen L, Zhao S, Hong FF. Mercerization of tubular bacterial nanocellulose for control of the size and performance of small-caliber vascular grafts. Chem Eng J 2022;428:131104. https://doi.org/10.1016/J.CEJ.2021.131104.
[205] Ahrem H, Pretzel D, Endres M, Conrad D, Courseau J, Müller H, et al. Laser-structured bacterial nanocellulose hydrogels support ingrowth and differentiation of chondrocytes and show potential as cartilage implants. Acta Biomater 2014;10:1341–53. https://doi.org/10.1016/j.actbio.2013.12.004.
[206] Nimeskern L, Martínez Ávila H, Sundberg J, Gatenholm P, Müller R, Stok KS. Mechanical evaluation of bacterial nanocellulose as an implant material for ear cartilage replacement. J Mech Behav Biomed Mater 2013;22:12–21. https://doi.org/10.1016/j.jmbbm.2013.03.005.
[207] Tanaka ML, Vest N, Ferguson CM, Gatenholm P. Comparison of biomechanical properties of native menisci and bacterial cellulose implant. Int J Polym Mater Polym Biomater 2014;63:891–7. https://doi.org/10.1080/00914037.2014.886226.
[208] Markstedt K, Mantas A, Tournier I, Martínez Ávila H, Hägg D, Gatenholm P. 3D bioprinting human chondrocytes with nanocellulose–alginate bioink for cartilage tissue engineering applications. Biomacromolecules 2015;16:1489–96. https://doi.org/10.1021/acs.biomac.5b00188.

[209] Jiji S, Udhayakumar S, Rose C, Muralidharan C, Kadirvelu K. Thymol enriched bacterial cellulose hydrogel as effective material for third degree burn wound repair. Int J Biol Macromol 2019;122:452–60. https://doi.org/10.1016/J.IJBIOMAC.2018.10.192.
[210] Silva RR, Raymundo-Pereira PA, Campos AM, Wilson D, Otoni CG, Barud HS, et al. Microbial nanocellulose adherent to human skin used in electrochemical sensors to detect metal ions and biomarkers in sweat. Talanta 2020;218:121153. https://doi.org/10.1016/J.TALANTA.2020.121153.
[211] Kalia S, Dufresne A, Cherian BM, Kaith BS, Avérous L, Njuguna J, et al. Cellulose-based bio- and nanocomposites: a review. Int J Polym Sci 2011;2011:837875. https://doi.org/10.1155/2011/837875.
[212] Sharip NS, Yasim-Anuar TAT, Norrrahim MNF, Shazleen SS, Nurazzi NM, Sapuan SM, et al. A review on nanocellulose composites in biomedical application. Compos Biomed Appl 2020:161–90. CRC Press.
[213] Althomali RH, Alamry KA, Hussein MA, Khan A, Alosaimi AM. A green nanocomposite based modified cellulose/TiO2/Cinnamon bark for the reduction of toxic organic compounds using spectrophotometric technique. J Mater Res Technol 2021;12:947–66. https://doi.org/10.1016/J.JMRT.2021.03.002.
[214] Zander NE, Dong H, Steele J, Grant JT. Metal cation cross-linked nanocellulose hydrogels as tissue engineering substrates. ACS Appl Mater Interfaces 2014;6:18502–10. https://doi.org/10.1021/am506007z.
[215] Saïdi L, Vilela C, Oliveira H, Silvestre AJD, Freire CSR. Poly(N-methacryloyl glycine)/nanocellulose composites as pH-sensitive systems for controlled release of diclofenac. Carbohydr Polym 2017;169:357–65. https://doi.org/10.1016/j.carbpol.2017.04.030.
[216] Tummala GK, Joffre T, Rojas R, Persson C, Mihranyan A. Strain-induced stiffening of nanocellulose-reinforced poly (vinyl alcohol) hydrogels mimicking collagenous soft tissues. Soft Matter 2017;13:3936–45.
[217] Hoeng F, Denneulin A, Bras J. Use of nanocellulose in printed electronics: a review. Nanoscale 2016;8:13131–54. https://doi.org/10.1039/c6nr03054h.
[218] Zhou C, Shi Q, Guo W, Terrell L, Qureshi AT, Hayes DJ, et al. Electrospun bio-nanocomposite scaffolds for bone tissue engineering by cellulose nanocrystals reinforcing maleic anhydride grafted PLA. ACS Appl Mater Interfaces 2013;5:3847–54. https://doi.org/10.1021/am4005072.
[219] Tang H, Butchosa N, Zhou Q. A transparent, hazy, and strong macroscopic ribbon of oriented cellulose nanofibrils bearing poly(ethylene glycol). Adv Mater 2015;27:2070–6. https://doi.org/10.1002/adma.201404565.
[220] Mukherjee T, Czaka M, Kao N, Gupta RK, Choi HJ, Bhattacharya S. Dispersion study of nanofibrillated cellulose based poly(butylene adipate-co-terephthalate) composites. Carbohydr Polym 2014;102:537–42. https://doi.org/10.1016/j.carbpol.2013.11.047.
[221] Li Y, Chen H, Liu D, Wang W, Liu Y, Zhou S. PH-responsive shape memory poly(ethylene glycol)-Poly(ε-caprolactone)-based polyurethane/cellulose nanocrystals nanocomposite. ACS Appl Mater Interfaces 2015;7:12988–99. https://doi.org/10.1021/acsami.5b02940.
[222] Kurihara T, Isogai A. Mechanism of TEMPO-oxidized cellulose nanofibril film reinforcement with poly(acrylamide). Cellulose 2015;22:2607–17. https://doi.org/10.1007/s10570-015-0680-5.
[223] Ma P, Jiang L, Hoch M, Dong W, Chen M. Reinforcement of transparent ethylene-co-vinyl acetate rubber by nanocrystalline cellulose. Eur Polym J 2015;66:47–56. https://doi.org/10.1016/j.eurpolymj.2015.01.037.
[224] Mariano M, El Kissi N, Dufresne A. Melt processing of cellulose nanocrystal reinforced polycarbonate from a masterbatch process. Eur Polym J 2015;69:208–23. https://doi.org/10.1016/j.eurpolymj.2015.06.007.
[225] Almasi H, Ghanbarzadeh B, Dehghannya J, Entezami AA, Asl AK. Novel nanocomposites based on fatty acid modified cellulose nanofibers/poly(lactic acid): morphological and physical properties. Food Packag Shelf Life 2015;5:21–31. https://doi.org/10.1016/j.fpsl.2015.04.003.
[226] Oun AA, Rhim JW. Preparation and characterization of sodium carboxymethyl cellulose/cotton linter cellulose nanofibril composite films. Carbohydr Polym 2015;127:101–9. https://doi.org/10.1016/j.carbpol.2015.03.073.
[227] Herrera N, Salaberria AM, Mathew AP, Oksman K. Plasticized polylactic acid nanocomposite films with cellulose and chitin nanocrystals prepared using extrusion and compression molding with two cooling rates: effects on mechanical, thermal and optical properties. Compos Part A Appl Sci Manuf 2016;83:89–97. https://doi.org/10.1016/j.compositesa.2015.05.024.
[228] Shanmugam K, Browne C. Nanocellulose and its composite films: applications, properties, fabrication methods, and their limitations. Nanoscale Process 2021:247–97. https://doi.org/10.1016/b978-0-12-820569-3.00010-4. Elsevier.
[229] Rosen CL, Steinberg GK, Demonte F, Delashaw JB, Lewis SB, Shaffrey ME, et al. Results of the prospective, randomized, multicenter clinical trial evaluating a biosynthesized cellulose graft for repair of dural defects. Neurosurgery 2011;69:1093–103. https://doi.org/10.1227/NEU.0b013e3182284aca.
[230] Xiao S, Gao R, Gao LK, Li J. Poly(vinyl alcohol) films reinforced with nanofibrillated cellulose (NFC) isolated from corn husk by high intensity ultrasonication. Carbohydr Polym 2015;136:1027–34. https://doi.org/10.1016/j.carbpol.2015.09.115.
[231] Ribeiro AS, Costa SM, Ferreira DP, Calhelha RC, Barros L, Stojković D, et al. Chitosan/nanocellulose electrospun fibers with enhanced antibacterial and antifungal activity for wound dressing applications. React Funct Polym 2021;159:104808. https://doi.org/10.1016/j.reactfunctpolym.2020.104808.
[232] Liu JC, Martin DJ, Moon RJ, Youngblood JP. Enhanced thermal stability of biomedical thermoplastic polyurethane with the addition of cellulose nanocrystals. J Appl Polym Sci 2015;132:1–8. https://doi.org/10.1002/app.41970.
[233] Larsson PA, Berglund LA, Wågberg L. Ductile all-cellulose nanocomposite films fabricated from core-shell structured cellulose nanofibrils. Biomacromolecules 2014;15:2218–23. https://doi.org/10.1021/bm500360c.
[234] Merindol R, Diabang S, Felix O, Roland T, Gauthier C, Decher G. Bio-inspired multiproperty materials: strong, self-healing, and transparent artificial wood nanostructures. ACS Nano 2015;9:1127–36. https://doi.org/10.1021/nn504334u.
[235] Abitbol T, Rivkin A, Cao Y, Nevo Y, Abraham E, Ben-Shalom T, et al. Nanocellulose, a tiny fiber with huge applications. Curr Opin Biotechnol 2016;39:76–88. https://doi.org/10.1016/j.copbio.2016.01.002.
[236] Mohd NH, Kargazadeh H, Miyamoto M, Uemiya S, Sharer N, Baharum A, et al. Aminosilanes grafted nanocrystalline cellulose from oil palm empty fruit bunch aerogel for carbon dioxide capture. J Mater Res Technol 2021;13:2287–96. https://doi.org/10.1016/J.JMRT.2021.06.018.
[237] Li J, Wang Y, Zhang L, Xu Z, Dai H, Wu W. Nanocellulose/gelatin composite cryogels for controlled drug release. ACS Sustain Chem Eng 2019;7:6381–9. https://doi.org/10.1021/acssuschemeng.9b00161.

[238] Tercjak A, Gutierrez J, Barud HS, Domeneguetti RR, Ribeiro SJL. Nano- and macroscale structural and mechanical properties of in situ synthesized bacterial cellulose/PEO-b-PPO-b-PEO biocomposites. ACS Appl Mater Interfaces 2015;7:4142–50. https://doi.org/10.1021/am508273x.
[239] Milwich M, Speck T, Speck O, Stegmaier T, Planck H. Biomimetics and technical textiles: solving engineering problems with the help of nature's wisdom 1. Am J Botany 2006. https://doi.org/10.3732/ajb.93.10.1455.
[240] Hasan KMF, Horváth G, Alpár T. Polymers potential natural fiber polymeric nanobiocomposites: a review. Polymers 2020. https://doi.org/10.3390/polym12051072. n.d.
[241] Teisala H, Tuominen M, Kuusipalo Teisala JH, Tuominen M, Kuusipalo J. Superhydrophobic coatings on cellulose-based materials: fabrication, properties, and applications. Adv Mater Interfaces 2013. https://doi.org/10.1002/admi.201300026.
[242] Heise K, Kontturi E, Allahverdiyeva Y, Tammelin T, Linder MB, Nonappa, et al. Nanocellulose: recent fundamental advances and emerging biological and biomimicking applications. Adv Mater 2021;33:2004349. https://doi.org/10.1002/adma.202004349.
[243] Liu K, Lin X, Chen L, Huang L, Cao S. Dual-functional chitosan-methylisothiazolinone/microfibrillated cellulose biocomposites for enhancing antibacterial and mechanical properties of agar films. Cellulose 2014. https://doi.org/10.1007/s10570-013-0145-7. n.d.
[244] Liu L, Kong F. Influence of nanocellulose on in vitro digestion of whey protein isolate. Carbohydr Polym 2019;210:399–411. https://doi.org/10.1016/J.CARBPOL.2019.01.071.
[245] Tchang N, Christian C, Per A, Larsson T, Wågberg L. Ultra porous nanocellulose aerogels as separation medium for mixtures of oil/water liquids. Cellulose 2012. https://doi.org/10.1007/s10570-011-9629-5. n.d.
[246] Shaabani A, Keshipour S, Hamidzad M, Seyyedhamzeh M. An efficient catalyst for room temperature aerobic oxidation of alcohols. J Chem Sci 2014;126:111–5. https://doi.org/10.1007/s12039-013-0535-2.
[247] Nadia Mohammad Padzil F, Hua Lee S, Ainun ZM, Lee CH, Abdullah LC. Materials potential of oil Palm empty fruit Bunch resources in nanocellulose hydrogel production for versatile applications: a review. Materials 2020. https://doi.org/10.3390/ma13051245.

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