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Review

Valorization of diverse waste-derived nanocellulose for multifaceted applications: A review

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ABSTRACT

The study underscores the urgent need for sustainable waste management by focusing on circular economy principles, government regulations, and public awareness to combat ecological threats, pollution, and climate change effects. It explores extracting nanocellulose from waste streams such as textile, paper, agricultural matter, wood, animal, and food waste, providing a detailed process framework. The emphasis is on waste-derived nanocellulose as a promising material for eco-friendly products. The research evaluates the primary mechanical and thermal properties of nanocellulose from various waste sources. For instance, cotton-derived nanocellulose has a modulus of 2.04–2.71 GPa, making it flexible for lightweight applications. Most waste-derived nanocelluloses have densities between 1550 and 1650 kg/m^3, offering strong, lightweight packaging support while enhancing biodegradability and moisture control. Crystallinity influences material usage: high crystallinity is ideal for packaging (e.g., softwood, hardwood), while low crystallinity suits textiles (e.g., cotton, bamboo). Nanocelluloses exhibit excellent thermal stability above 200 °C, useful for flame-retardant coatings, insulation, and polymer reinforcement. The research provides a comprehensive guide for selecting nanocellulose materials, highlighting their potential across industries like packaging, biomedical, textiles, apparel, and electronics, promoting sustainable innovation and a more eco-conscious future.

1. Introduction

Waste is a pressing global issue that has severe environmental consequences. The lack of proper waste management poses a threat to ecosystems, human health, and the environment. Landfills emit pollutants, such as methane, which contribute to climate change [1]. Water bodies become contaminated with chemicals and leachates, putting aquatic life and communities in danger. Disposing of waste in natural environments worsens the problem, leading to marine pollution and resource depletion. Improper waste management process releases pollutants and greenhouse gases, exacerbating air pollution and climate change. Sustainable waste management practices are crucial to address these issues. This includes waste reduction, recycling, and the promotion of eco-friendly materials. A shift towards a circular economy, in combination with public awareness and government regulations, can mitigate the environmental effects of waste mismanagement and establish a more sustainable future. Globally, the annual amount of municipal solid waste generated by the world is 2.01 billion tonnes, and it is anticipated that this figure will increase by approximately 70 % to reach 3.4 billion tonnes by 2050 [2]. Fig. 1 shows the annual spending on waste management by the UK government from 2010 to 2019. In 2019, the costs for waste management amounted to approximately £11.65 billion, which accounts for a considerable portion of the national budget [3,4].

This research pioneers an innovative approach to identify optimal applications for diverse waste-derived nanocellulose types, surpassing conventional analyses. In the first step, the initial exploration meticulously catalogs potential applications, investigates, and summarizes attributes. Subsequently, it introduces a groundbreaking quantitative analysis, revealing relationships between material properties and application attributes. A distinctive contribution is the presentation of comprehensive numerical summaries of waste-derived nanocellulose material properties across five characteristics: modulus of elasticity,

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tensile strength, density, crystallinity, and thermal stability. This research breaks new ground by elucidating intricate relationships between each nanocellulose variant and its specific application, ushering in a transformative contribution to the field. The methodology not only enhances precision but also marks a significant departure, promising a paradigm shift in our understanding of waste-derived nanocellulose applications.

1.1. Reduce-recycle-reuse

The concept of the circular economy, emphasizing "reduce, recycle, and reuse," stands as a pivotal strategy to mitigate waste production and enhance resource efficiency. These principles are fundamental in establishing a closed-loop system that continually regenerates materials, reducing environmental impacts and conserving resources. Circular economy targets, which are among the most commonly applied in economic systems, can be grouped into five main areas of application: efficiency, recycling, recovery, reduction, and design (Fig. 2). These areas are highly interconnected, often overlapping in practice; for example, waste reduction initiatives can simultaneously improve material efficiency, while design choices can influence all other target areas. This interconnectedness is visually conveyed in Fig. 2 by the overlapping cycles representing these application areas [5]. By implementing approaches like waste prevention, recycling programs, and promoting responsible consumption, a shift towards a more sustainable economic model becomes feasible [6]. Furthermore, the significant applications of nanocellulose across various industries present a compelling opportunity to advance sustainability by deriving nanocellulose from recycled waste materials. This approach not only promotes the circular economy but also contributes to waste reduction while yielding cost-effective, high-quality nanocellulose for valuable products [7].

Government initiatives are crucial in driving sustainable waste management practices and fostering a circular economy. The UK government's "Resources and Waste Strategy for England: Monitoring and Evaluation" exemplifies a commitment to raising recycling rates and reducing landfill waste through funding recycling infrastructure, research, and awareness campaigns [8]. These efforts aim to promote resource efficiency and waste valorization, aligning with circular economy principles. The circular economy framework emphasizes resource extension and waste minimization by implementing strategies such as redesign, reuse, repair, recycling, and upcycling. These strategies not only prevent waste but also encourage the design of durable, reusable, and recyclable products, thus reducing reliance on virgin resources and promoting sustainability [9].

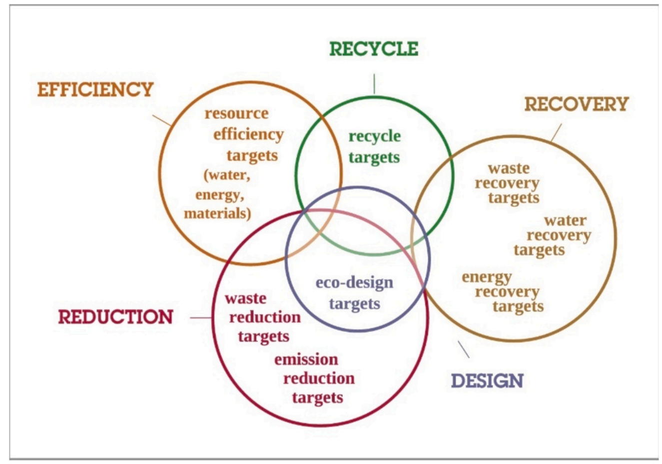

Fig. 2. Interconnected Targets of the Circular Economy: Areas of Application and Overlap [5].

Nanocellulose, sourced from waste materials, represents a sustainable solution due to its renewability and unique properties. Studies have demonstrated the feasibility of producing high-quality nanocellulose from various waste sources [10]. These studies highlight the potential of waste materials as valuable sources for nanocellulose production, offering environmentally friendly alternatives for multiple applications. The utilization of waste materials for nanocellulose production involves several key steps, from collection and preprocessing to product development and applications [11]. This process aligns with circular economy principles by transforming waste into valuable and sustainable products, contributing to waste valorization and the development of eco-friendly materials.

The utilization of waste materials to produce valuable products, particularly nanocellulose, involves several key steps that are of great academic interest as shown in Fig. 3. These steps include collection and pre-processing, elimination of lignin, and purification, nanocellulose extraction, post-treatment and functionalization, and product development and applications. In the first step, waste materials such as agricultural residues, forestry residues, or industrial by-products are collected and prepared for further processing, which may involve cleaning, sorting, and size reduction. In the second step, delignification

Fig. 1. Waste management spending by the government in the United Kingdom (UK) 2010-2019 [4].

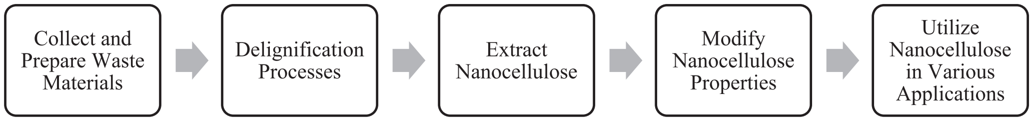

Fig. 3. process flowchart: converting waste materials to nanocellulose and its utilization.

processes are employed to remove lignin and hemicellulose from the collected waste materials, leaving behind cellulose-rich fibers. Various mechanical and chemical methods are utilized in the third step to extract nanocellulose from the purified cellulose fibers, which may include high-pressure homogenization, microfluidization, ultrasonication, and enzymatic or acid hydrolysis. In the fourth step, the extracted nanocellulose may undergo additional processing steps to modify its properties or introduce specific functionalities. Finally, in the fifth step, the nanocellulose obtained from waste materials can be utilized in various industries and applications such as biomedical applications, packaging materials, the paper and textile industry, and composites and coatings [12,13].

The transformation of waste materials into valuable and sustainable products through the extraction of nanocellulose is a promising research area that continues to be explored and optimized for waste valorization and the development of eco-friendly materials. Therefore, further research on the production of nanocellulose from recycled materials is essential for the development of sustainable and eco-friendly materials.

1.2. *Structural organization of nanocellulose*

Nanocellulose, a remarkable material with at least one dimension in the nanoscale, is revolutionizing various industries with its exceptional properties [14]. Derived from cellulose-rich waste materials, nanocellulose presents a sustainable and eco-friendly alternative, addressing the pressing concerns of resource depletion and waste accumulation [15,16]. Its inherent characteristics, including high strength, biodegradability, and versatility, make it highly desirable for a wide range of applications across different sectors [17]. The production process of waste-derived nanocellulose involves several intricate steps aimed at transforming cellulose-rich waste materials into nanoscale cellulose particles. Initially, the raw material undergoes pretreatment to remove non-cellulosic components and enhance the accessibility of cellulose fibers [18]. This pretreatment process may involve chemical treatments, such as acid or alkali hydrolysis, or mechanical processes like grinding or milling [19].

Following pretreatment, cellulose extraction is carried out to isolate the cellulose fibers from the pretreated material. Mechanical methods, such as grinding or milling, may be employed to physically separate the cellulose fibers, while chemical methods, such as acid hydrolysis or enzymatic digestion, dissolve or degrade non-cellulosic components, leaving behind purified cellulose fibers. Once the cellulose fibers are extracted, they are further processed to obtain nanocellulose particles with dimensions in the nanometer scale. Mechanical methods involve applying high shear forces to disintegrate the cellulose fibers into nanoscale particles using techniques such as high-pressure homogenization or ultrasonication. Alternatively, chemical methods, such as acid hydrolysis or oxidation, depolymerize the cellulose chains to produce nanocellulose particles [20,21].

Throughout the production process, rigorous quality control measures are implemented to ensure the purity, uniformity, and functionality of the nanocellulose product. Characterization techniques such as electron microscopy, atomic force microscopy, X-ray diffraction, and spectroscopic methods are utilized to analyze the physicochemical properties of the nanocellulose particles. The classification of nanocellulose is based on dimensions as shown in Table 1 and Fig. 4.

The morphology of CMF from untreated hemp stalks (Fig. 5a) revealed fibers strongly bonded with a compact and rough surface. Following the application of alkali treatment, notable alterations were observed, as illustrated in Fig. 5b, where the fibers appeared separated into bundled micro-sized structures. Subsequent bleaching, as depicted in Fig. 5c and d, resulted in individualized single microfibers possessing a clean and smooth surface, measuring 16.96 ± 1.33 μm in diameter [26]. Remarkably, this diameter surpasses values documented in the other research for CMF extracted from various sources, including *Hibiscus sabdariffa* (10.04 μm) [27], Alfa fibers (10 μm) [28], and grass (6 μm) [29].

The morphologies of pineapple leaves and the resulting CNFs are shown in Fig. 6. Initially, pineapple leaves exhibit a rod-like shape due to the presence of lignin, hemicelluloses, and pectin enveloping cellulose nanofibers (Fig. 6a). Alkali treatment increases surface roughness by partially removing these substances (Fig. 6b), while bleaching results in partial defibrillation, producing a smoother surface (Fig. 6c). Cellulose microfibrils with a diameter of 3.27–4.78 μm, further reduced to 80.5–83.7 nm after 1.5 h of ball milling (Fig. 6d). Scanning electron microscope (SEM) images demonstrate successful isolation of CNFs from pineapple leaves, exhibiting a long fiber-like network [30].

The morphologies of degreasing cotton, waste cotton cloth fibers, and the resulting CNCs are depicted in Fig. 7 [31]. Image representations exhibit degreasing cotton and waste cotton cloth, the former comprising medical pure cotton, and the latter an aged and printed pure cotton bed sheet that underwent various physical and chemical treatments. Despite variations in spinning and dyeing, SEM images (Fig. 7a and b) indicate no significant morphological differentiation between degreasing cotton and waste cotton cloth fibers, both showcasing flat, spiral shapes with a diameter of 50 μm and a smooth, uniform surface. SEM images of celluloses derived from both materials (Fig. 7c and d) demonstrate swelling due to alkali treatment, displaying rough surfaces and disrupted outer layers, attributed to impurity removal during processing. Subsequent hydrolysis produces CNCs with rod-like structures (Fig. 7e and f). Transmission electron microscope (TEM) images show smaller and finer CNCs from degreasing cotton, with length and diameter ranges of 17 to 230 nm and 2 to 25 nm, respectively, compared to CNCs from waste cotton cloth (28 to 470 nm length, 3 to 35 nm diameter). The aspect ratios for degreasing cotton and waste cotton cloth CNCs are 12 ± 10 and 17 ± 15, respectively, indicating potential reinforcing effects for composite materials [32]. The SEM depiction of BNC generated by Acetobacter (Fig. 8 a and b) unveils cellulose fibrils that demonstrate merging, potentially arising from the formation of hydrogen bonds during the drying phase. The resultant three-dimensional structure

Table 1
Nanocellulose types: characteristics.

Nanocellulose	Diameter [mm]	Length [mm]	Shape	Surface area [m^2/g]	References
Cellulose microfibers (CMF)	10	>10	Long, slender fibers	$<10^{-6}$	[22]
Cellulose nanofibrils (CNF)	5–60	Several micrometers	Fiber shape	~100	[23]
Cellulose Nanocrystalline (CNC)	5–70	Several micrometers	Needle-shaped	~200	[24]
Bacterial nano-cellulose (BNC)	20–100	Several micrometers	Fiber shape	~1500	[25]

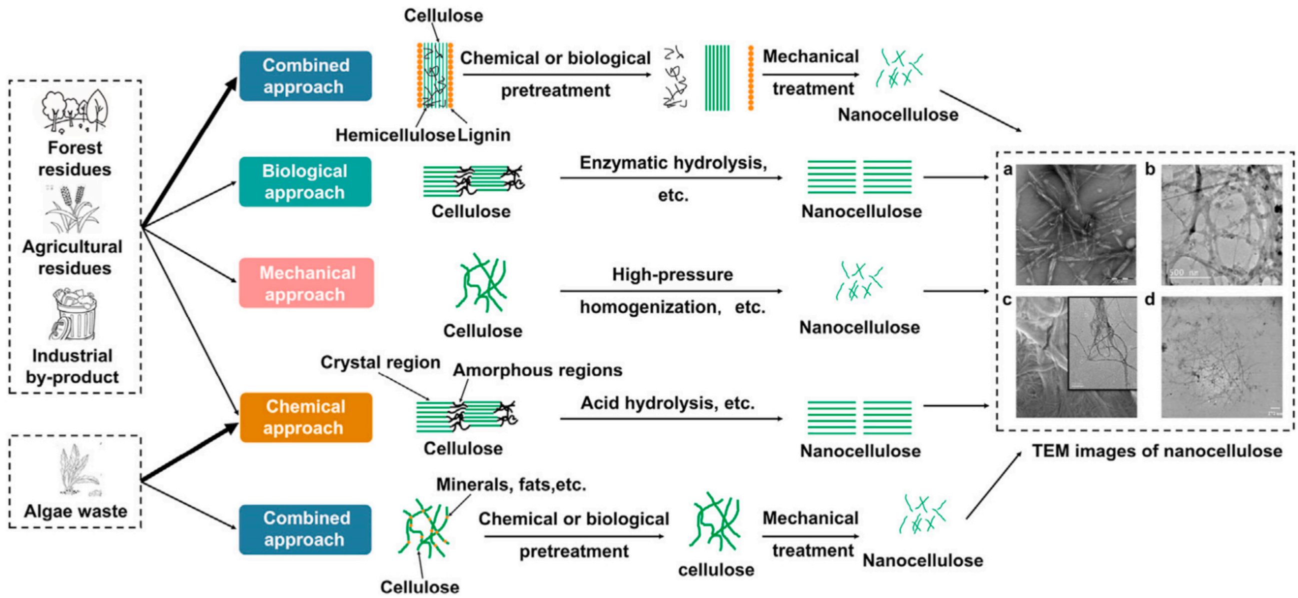

Fig. 4. Schematic synthesis pathways of nanocellulose from various biomass sources [21].

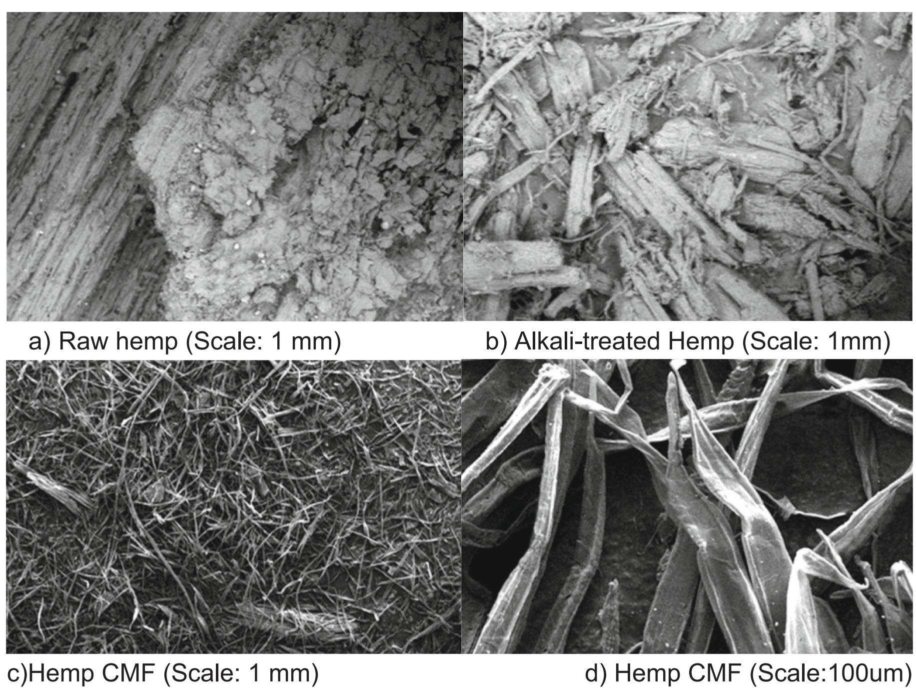

Fig. 5. SEM images of the extracted CMF from hemp stalks [26].

exhibits an approximate thickness of 40 μm. Upon meticulous examination, singular fibrils, ranging from several microns to millimeters in length, become apparent. Altering the configuration of the desiccated BNC pellicle with tweezers offers a closer look at the fiber dimensions, revealing each fiber to possess a 5 nm diameter along the pellicle periphery [33].

2. The potential applications of nanocellulose from waste materials

The application of nanocellulose derived from waste materials has gained significant interest due to its potential to address environmental concerns and offer sustainable solutions in various industries. Waste materials such as wood, textile, paper, agricultural, animal, and food can be transformed into nanocellulose, a material with remarkable mechanical properties, renewability, and biocompatibility. Numerous investigations have been conducted on the broad spectrum of uses of nanocellulose generated from waste materials.

2.1. Food packaging and additives applications

Nanocellulose has emerged as a sustainable substitute for petroleum-derived packaging materials, offering remarkable barrier properties, mechanical durability, and biodegradability [34]. The packaging industry benefits from the unique characteristics of nanocellulose, including its high crystallinity index, high aspect ratio, and high thermal

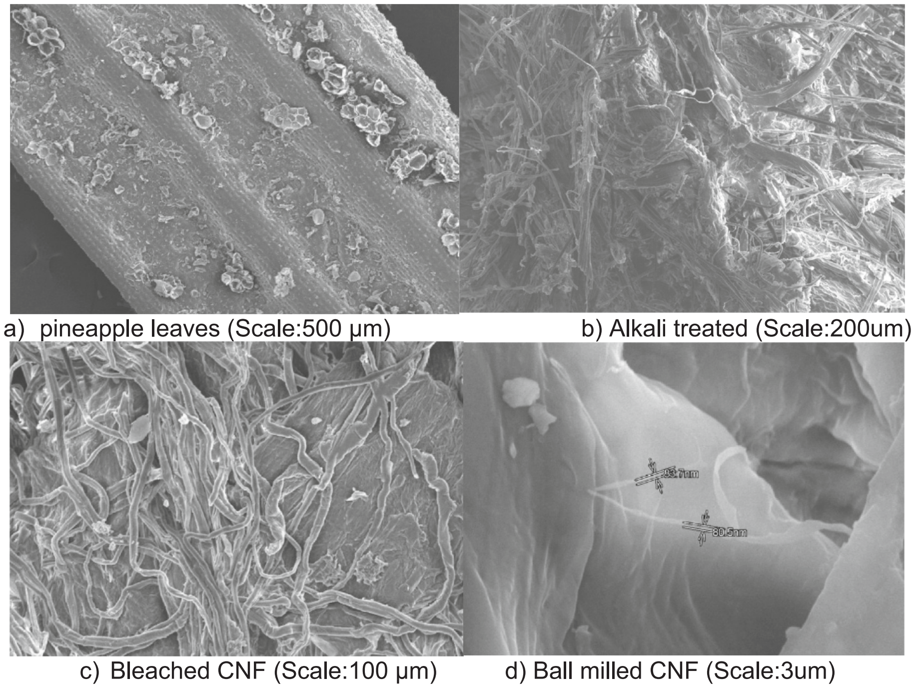

Fig. 6. SEM images of the extracted CNF from pineapple leaves [30].

stability, making it well-suited for various applications in this sector [35]. The various sources, such as cardboard [36], corn stover [37], pineapple leaf [35], banana fiber and cowdung [38], and silk-nanocellulose [39], demonstrate the versatility and potential applications of nanocellulose in packaging materials (Fig. 9a). Further research and development are needed to fully realize the potential of this eco-friendly material in the packaging industry. Its biodegradable nature ensures that packaging materials made from nanocellulose can be easily disposed of without causing harm to the environment [40]. Additionally, its robust mechanical strength provides durability and protection for packaged goods [41]. With its resistance to moisture, nanocellulose-based packaging materials offer a reliable barrier against environmental factors that could potentially compromise the integrity of packaged items [42]. However, realizing the complete potential requires further research and development to address challenges related to raw material selection, extraction methods, product design, and life cycle considerations [43]. Rice straw and oil palm empty fruit bunches are identified as particularly promising sources of raw nanocellulose [44]. The utilization of nanocellulose extends to bioplastic bags, especially in enhancing the shelf-life of exotic fruits during transport and distribution. Incorporating nanocellulose from rice straw and palm empty fruit bunch into bioplastic bags leads to significant enhancements. Numerical data shows a 23.30 % increase in tensile strength and a 24.76 % increase in elongation with empty fruit bunch nanocellulose. However, challenges emerge as the water vapor transmission rate rises in comparison to polypropylene plastic bags, necessitating further optimization [43].

The incorporation of nanocellulose into polymer matrices is driven by both weak (Van der Waals forces and hydrogen bonding) and strong (covalent) intermolecular linkages, resulting in materials with optimal elasticity and tensile strength [45]. Furthermore, the valorization of oil palm waste through a multi-product cascade biorefinery approach showcased the extraction of bioactive compounds and the production of CNF food packaging. The CNF-reinforced polyvinyl alcohol films demonstrated increased tensile strength, mechanical resistance, and improved barrier capacity against water vapor. Additionally, incorporating a bioactive extract into the films resulted in enhanced UV-light barrier properties and antioxidant capacity, showcasing potential applications in active food packaging [46].

An important application of nanocellulose is in the realm of food additives, where it serves as a stabilizer, dietary fiber, thickener, flavor carrier, and suspension stabilizer. Its gel-like structure possesses excellent rheological properties, making it a desirable choice for various food products like fillings, creams, ice cream, chips, wafers, soups, and puddings [47]. In the context of food additives, nanocellulose has proven versatile, acting as a substitute for fats and stabilizing oil emulsions, enhancing the texture and stability of food items [48]. Additionally, the polymeric nanostructure of nanocellulose derived from banana has been leveraged to absorb natural antioxidants, such as polyphenols, preventing food spoilage and prolonging product shelf life [49,50]. Innovative approaches, like using Ag-decorated nanocellulose for detecting hazardous residues in various food matrices through surface-enhanced Raman spectroscopy techniques, have also been explored [51].

The utility of nanocellulose as a food additive extends to functional foods, influencing characteristics like retrogradation, gelatinization, and pasting of starch. CNC can increase peak viscosity and decrease setback values in different starches, showcasing their potential in controlling starch retrogradation. In the study, CNC incorporation led to approximately 15 %, 20 %, and 18 % elevation in peak viscosity for normal maize starch, sweet potato starch, and waxy starch, respectively. Moreover, CNC reduced setback values of sweet potato starch by approximately 10 %, indicating its effectiveness in delaying short-term retrogradation [52].

Furthermore, nanocellulose has been investigated for its impact on intestinal digestion, mineral adsorption, and potential reduction in triglycerides hydrolysis, indicating its influence on nutrient digestion and absorption [53]. Results from such studies show a notable 50 % decrease in triglycerides hydrolysis, suggesting that when introduced into the system, nanocellulose adheres to fat droplets, interfering with lipase activity [53]. The application of CNCs as food additives holds promise in mitigating the negative effects of high-fat products on human health by substituting oils, thus enhancing food safety and quality. Growing consumer preference for natural products has elevated the demand for sustainable and health-conscious food systems. Nanocellulose, a non-caloric dietary fiber, emerges as a promising natural source for food additives. Combining nanocellulose with natural antioxidants yields a

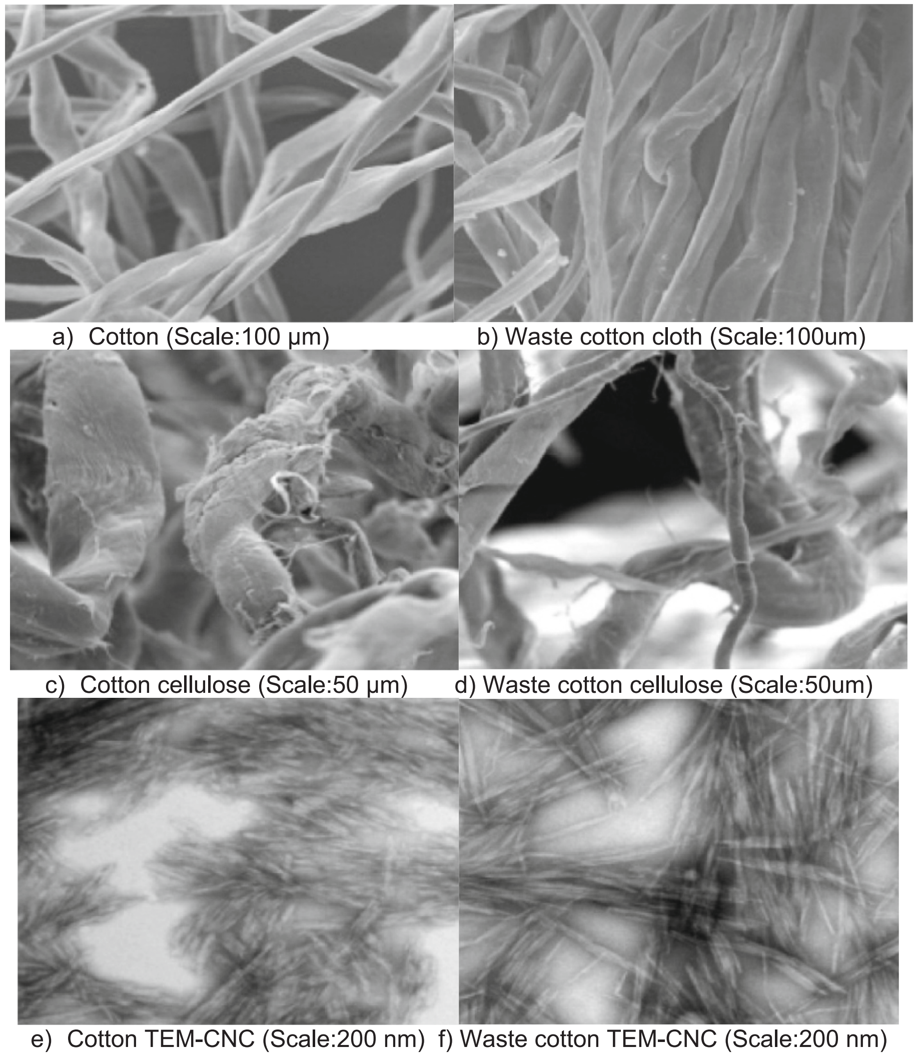

Fig. 7. SEM images extracted CNC from cotton [31].

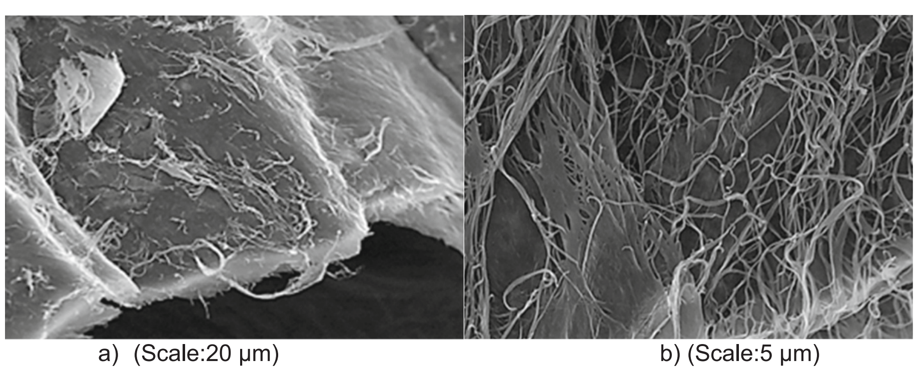

Fig. 8. SEM images extracted BNC from Acetobacter [33].

polyphenolic-nanocellulose complex with outstanding antioxidant properties and heat resistance, potentially replacing artificial preservatives [50]. Fig. 10 provides a detailed overview of how nanoparticles influence different food packaging types, highlighting their role in enhancing packaging performance and functionality. Table 2 provides a comprehensive summary of nanocellulose applications in food packaging and additives, highlighting key findings, numerical results, and relevant references across various studies.

2.2. Biomedical applications

Nanocellulose derived from abundant agricultural and industrial waste streams shows tremendous potential for various biomedical uses owing to its multifaceted and customizable properties [54–58]. This eco-friendly material exhibits high biocompatibility for safe interaction with tissues alongside biodegradability and cost-effectiveness rendering it economically viable [59–61]. The mechanical strength of nanocellulose ensures structural integrity while its tunable porosity enables

Fig. 9. Applications of waste-derived nanocellulose.

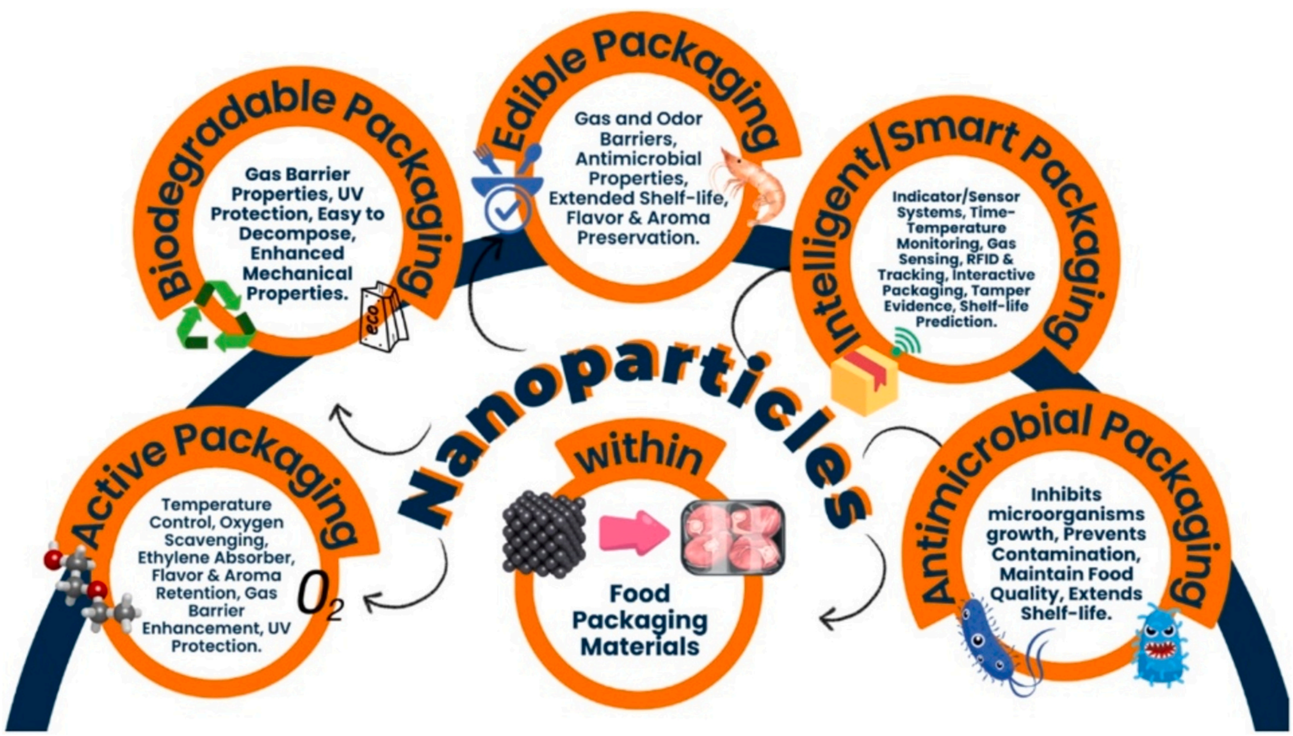

Fig. 10. Integration of nanoparticle technology with diverse food packaging materials and methods [49].

specialized applications [62].

Specific waste sources identified for biomedical nanocellulose include natural silk [39], sugarcane bagasse [63,64], and pineapple leaves [53]. Extensive research on these residues points to versatile functionality for wound healing constructs (Fig. 9b), drug delivery systems (Fig. 9c), cosmetic (Fig. 9d) and tissue engineering scaffolds (Fig. 9e). For instance, the biodegradability of nanocellulose ensures safe integration of implants or grafts that naturally break down over time, while its chemical stability promotes compatibility with bodily tissues.

2.2.1. Wound healing

Research shows the promise of nanocellulose derived from abundant agricultural and forestry residues to enable more sustainable and effective solutions for wound treatment applications [65,66]. The resulting material demonstrates favorable properties for wound healing, including high moisture retention capacity alongside mechanical strength and flexibility to conform to wound sites [67,68]. Fig. 11 illustrates the use of nanocellulose, derived from agricultural by-products, in wound healing and drug delivery applications [68].

Specific waste sources of nanocellulose explored for wound healing include wood pulp, sugarcane bagasse, and pineapple leaves. For instance, wood-derived CNF hydrogel dressings demonstrated accelerated epithelialization of split-thickness skin graft donor sites compared to a commercial wound healing product in clinical testing on burn patients. The high fluid absorbency ensured suitability for exudative wounds while the translucency enabled visual assessments of healing progress [69].

Beyond direct applications of nanocellulose, recent advances also showcase the potential of agricultural waste-derived nanocellulose composites for wound healing. Incorporating natural antibacterial and anti-inflammatory compounds like propolis into NFC mats imparted effectiveness against *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*) [70]. Nanocellulose sponges with 4 % propolis extract eradicated *S. aureus* and methicillin-resistant *S. aureus*. Another study revealed TEMPO-oxidized NFC loaded with the antibiotic tetracycline accelerated wound closure in rat skin defects while reducing bacterial loads.[88] Animal-derived nanocellulose, in the form of *Styela clava*

Table 2
Summary of nanocellulose applications in food packaging and additives.

Material source	Key findings	Numerical results	Ref
Cardboard, corn stover, pineapple leaf, banana fiber, cowdung, silk-nanocellulose	Demonstrated versatility and potential in packaging applications due to high crystallinity, aspect ratio, and thermal stability.	–	[35,39]
Rice straw and oil palm empty fruit bunches	Identified as promising sources of raw nanocellulose for bioplastic bags, enhancing the shelf-life of exotic fruits.	23.30 % increase in tensile strength and 24.76 % increase in elongation with palm nanocellulose.	[43,44]
Oil palm waste	Used in a multi-product cascade biorefinery approach for CNF food packaging, enhancing mechanical and barrier properties.	–	[46]
Nanocellulose as food additive	Acts as a stabilizer, thickener, flavor carrier, and enhances the texture of food products; improves starch retrogradation control.	15 %-20 % increase in peak viscosity for starches; 10 % reduction in setback values for sweet potato starch.	[47,52]
Nanocellulose in food digestion	Influences nutrient digestion and absorption, reduces triglyceride hydrolysis	50 % decrease in triglycerides hydrolysis.	[53]
Polyphenolic-nanocellulose complex	Combines nanocellulose with natural antioxidants, providing antioxidant properties and heat resistance.	–	[50]
Ag-decorated nanocellulose	Explored for detecting hazardous residues in food matrices using surface-enhanced Raman spectroscopy.	–	[51]

cellulose membranes alone or combined with alginate/selenium, demonstrated improved healing in surgically induced wounds in both normal and streptozotocin-induced diabetic rats [71,72].

2.2.2. Drug delivery

Nanocellulose, with its high surface area, biocompatibility, and tunable surface properties, shows promise as a drug delivery carrier. A significant reserve of nanocellulose is derived from the residual biomass of agricultural and forest waste. The acquisition of nanocellulose from these discarded resources offers environmental benefits and supports sustainability initiatives [73,74]. Nanocellulose is commonly prepared from waste materials through acid hydrolysis, enzymatic hydrolysis, oxidation hydrolysis, and mechanical processing to remove non-cellulosic components [75]. The resulting CNC and CNF possess high drug loading capacity. For example, CNC/drug nanoparticles displayed over 90 % drug encapsulation efficiency at a 1:5 mass ratio of CNC to drug [76].

Surface-modified CNC shows improved drug loading and release control compared to pure CNC. Soy protein isolate-CNC nanoparticles provided sustained release of curcumin over 24 h in a simulated gastrointestinal model [77]. Cancer drug 5-fluorouracil-loaded NCC nanoparticles exhibited dose-dependent toxicity in colorectal cancer cells. After 36 h, 80 % of the loaded drug was released through a combination of swelling, dissolution, and diffusion mechanisms [78]. Beyond nanoparticles, nanocellulose from waste biomass has been incorporated into other drug formulations including tablets, aerogels, hydrogels, and membranes [79]. Collectively, these systems demonstrate release times spanning minutes to days, providing versatility for diverse administration routes and delivery applications [80].

2.2.3. 3D-bioprinting

Various bioprinting technologies, such as inkjet, laser-assisted, and extrusion-based methods, have significantly advanced tissue engineering. However, these methods present challenges, necessitating bioinks with specific rheological properties to balance biological functionality and printing fidelity. The mechanical strength of the bioink is crucial for creating tissues that match native tissue properties [81]. Nanocellulose, sourced from waste materials, is emerging as an ideal bioink due to its inherent rheological characteristics, biocompatibility, and sustainability [82]. With cellulose being the most abundant polymer in nature, nanocellulose in various forms has exceptional potential for bioink development, offering cost-effectiveness and printability for 3D bioprinting applications [83].

The versatility of nanocellulose in tissue engineering is evident from various studies, showcasing its potential in 3D bioprinting applications for blood vessels, bone, cartilage, skeletal muscle, neural, dermal, and vascular tissue scaffolds [84]he combination of nanocellulose with

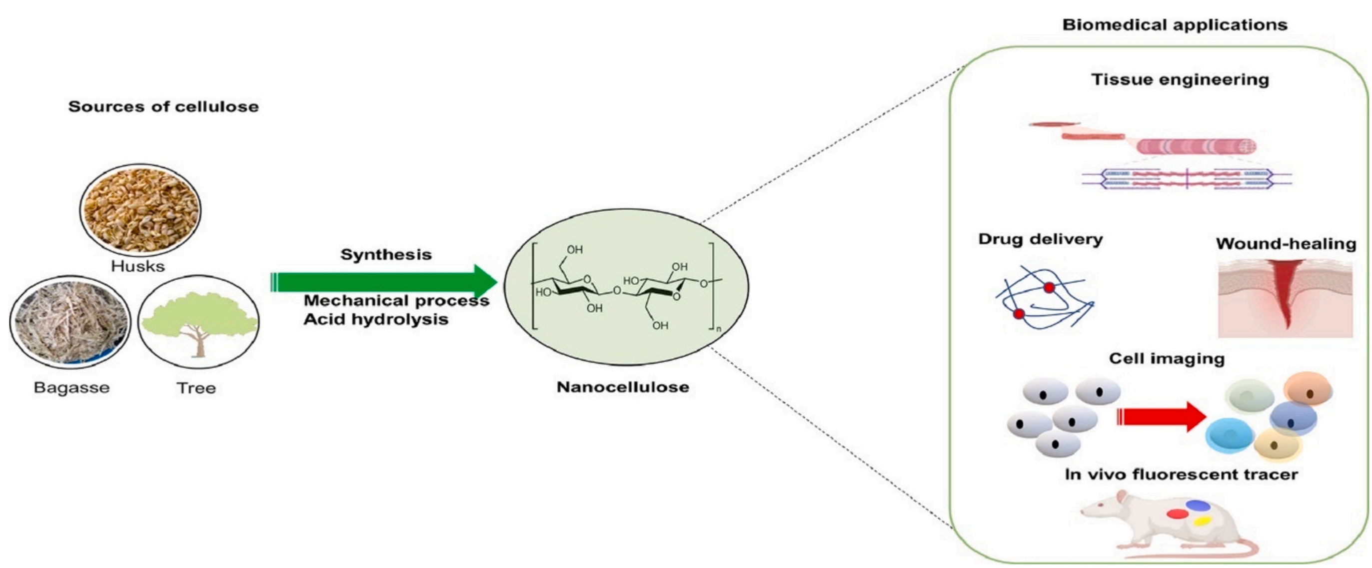

Fig. 11. Nanocellulose from agricultural biowaste: applications in wound healing and drug delivery [68].

alginate, a widely used biomaterial, proves effective in addressing challenges such as poor cross-linking potential and moderate cell adhesion, leading to enhanced cell viability, tensile strength, cellular proliferation, and improved cell adhesion capacity [85]. The success of nanocellulose-based bioinks lies in their ability to meet the mechanical demands of target tissues. Composites of nanocellulose and alginate have demonstrated excellent tissue viability, precise printing resolution, and enhanced cell proliferation [86]. These bio inks have successfully synthesized complex structures, such as vascularized bone tissue [87], cartilage [88], and entire vertebral bodies [89].

Studies focusing on nanocellulose-based bio inks consistently demonstrate positive results, with one study combining nanocellulose and alginate for cartilage tissue engineering reporting high human chondrocyte viability (86 %) after a 7-day culture [86]. The composite hydrogel, exhibiting shear-thinning behavior, enables the printing of anatomically shaped cartilage constructs, highlighting the potential for personalized tissue engineering [90].

In bone tissue engineering, nanocellulose alginate bioinks have been instrumental in synthesizing vascularized bone tissue with high tissue viability. Studies using nanocellulose-alginate bio inks reinforced with other biomaterials, such as chitin [91], gelatin [92], and hydroxyapatite [93], have successfully constructed composite scaffolds for 3D bioprinting of bone tissue.

The application of nanocellulose in neural, dermal, and vascular tissue engineering has demonstrated promising results. Studies using nanocellulose-carbon nanotube composites have shown enhanced neuroblastoma cell adhesion, differentiation, and proliferation, with minimal impact on cell viability [84]. Furthermore, the incorporation of nanocellulose in aortic valve conduits and vascular architecture has showcased its potential for cardiovascular tissue engineering [94].

The efficacy of silk fibroin nanofibers, produced by mechanically grinding degummed silkworm silk fibers, was evaluated as additives in bioinks for extrusion-based 3D bioprinting. These nanofibers, which can be sterilized through autoclaving, enhanced the shear-thinning properties of polymeric aqueous solutions without relying on electric charges or cross-linkable components. Incorporating the nanofibers into bioinks improved the precision of hydrogel constructs during printing, resulting in structures that closely matched design specifications. Furthermore, mammalian cells embedded in these constructs maintained over 85 % viability, and the presence of nanofibers did not alter cell morphology. Overall, the findings highlight the significant potential of silk fibroin nanofibers in enhancing the performance of bioinks for 3D bioprinting applications [95]. Waste-derived nanocellulose from silkworm silk fibroin serves as a promising additive in bioinks for 3D bioprinting. Obtained through the mechanical disintegration of degummed silk fibers, silk fibroin nanofibers (SFNFs) enhance shear thinning in various polymer solutions. SFNFs improve fidelity in 3D hydrogel constructs, showcasing versatility without compromising cell viability. The results suggest SFNFs as a bioink additive, enhancing printability (92.5-92.7 % cell viability). Fig. 12 depicts the role of silk fibroin nanofibers, derived from degummed silkworm silk fibers, in improving bio-inks used for 3D bioprinting. The figure illustrates how these nanofibers contribute to better fidelity in hydrogel constructs and maintain high cell viability, showcasing their effectiveness as bio-ink additives. Fig. 13 shows ear shapes obtained from 1.5 *w*/*v*% HA-Ph inks, one free of SFNFs and the other containing 1.0 *w*/*v*% SFNFs [95].

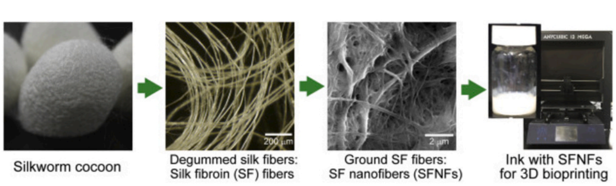

Fig. 12. Images showing silkworm cocoon, degummed silk fibroin fibers, SFNFs from ground silk fibers, and SFNFs-based ink for 3D bioprinting [95].

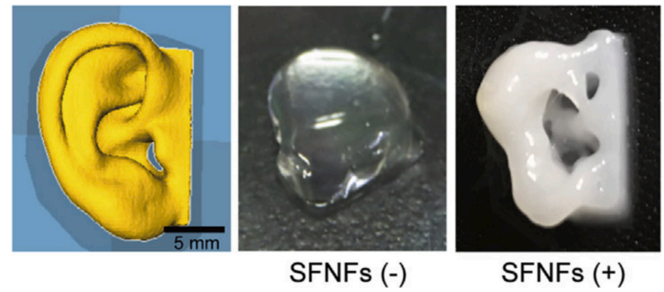

Fig. 13. Comparative ear-shaped constructs from HA-Ph inks with and without SFNFs [95].

2.2.4. Cosmetic

Nanocellulose, with nano-sized cellulose fibers, is gaining significant attention as a renewable and highly functional additive for cosmetics formulations. Cosmetic applications of nanocellulose include:

Nanocellulose can stabilize emulsions, including creams, lotions, and fragrance delivery systems, through Pickering stabilization. The high surface area of cellulose nanoparticles allows them to adsorb strongly to oil-water interfaces, forming a mechanically rigid barrier layer to suspend oil droplets [96].

In the realm of unbleached nanocellulose derived from bamboo waste, the process involves subjecting bamboo shoots to alkali treatment for delignification. Following this, High-Pressure Homogenization is employed to produce nanoparticles. Polyethylene emulsions, containing 0.3 % (*w*/*w*) nanoparticles and formulated with a 1:9 dodecane/water ratio (*v*/*v*), demonstrated stability without creaming for 30 days. This stability remained consistent across a pH range from 3.0 to 9.0 and temperatures ranging from 4 °C to 50 °C [97].

Furthermore, in stabilizing poly (*methyl methacrylate*) latex, when coated with methyl CNC-coated, superior emulsion stabilization properties were exhibited by the BNC: CNC formulation in comparison to dry commercial celluloses. Coalescence and creaming were successfully prevented for an extended period of 90 days at a concentration of 0.50 % [98]. The high surface area and reactivity of cellulose nanofibers also allow for the loading and sustained release of cosmetic active ingredients. For example, microbial nanocellulose adsorbed skin tanning agent dihydroxyacetone (DHA) in its fibrous network. This system slowly released DHA over time while preventing losses from leaching and undesirable smells that occur in conventional DHA creams [99].

Flexible nanocellulose films show promise as substrates for transdermal patches to deliver cosmetic ingredients like skin whiteners, wrinkle treatments, and acne medications over prolonged periods [100]. The composite film, incorporating BNC, demonstrated a significantly elevated Young's modulus, reaching 28 GPa [101]. This superiority over other composites, particularly those based on fibrillated kraft pulp, was attributed to the higher crystallinity, purity, aspect ratio, and uniform size of bacterial nanocellulose [102].

Table 3 offers an extensive overview of the applications of nanocellulose in the biomedical field.

2.3. Textiles

2.3.1. Textiles and apparel

Nanocellulose offers various benefits in the textile industry (Fig. 9f), such as improved performance and sustainability. It can be used as a coating or additive to enhance fabric properties like strength, wrinkle resistance, UV protection, and moisture management. Studies have explored different materials as sources of nanocellulose. For cotton fabrics, nanocellulose derived from agricultural waste materials like rice straw and banana stem has shown improvements in mechanical properties, dye uptake, water absorbency, and air permeability [103,104]. Cotton waste itself has been used to produce nanocellulose-reinforced

Table 3
Summary of nanocellulose applications in biomedical.

Material source	Application	Key findings	Numerical results	Ref
Wood pulp	Wound healing	CNF hydrogel dressings showed accelerated epithelialization compared to commercial products.	High fluid absorbency; translucency for visual assessment	[69]
Sugarcane bagasse	Wound healing	Effective for wound healing; potential for integration into composite materials.	Not specified	[65,66]
Pineapple leaves	Wound healing	Demonstrates favorable properties for wound treatment.	Not specified	[67,68]
Soy protein	Drug delivery	Effective for sustained release in a gastrointestinal model. Dose-dependent toxicity in colorectal cancer cells; significant drug release.	Release of curcumin over 24 h 80 % drug release after 36 h	[77]
Nanocellulose + alginate (cartilage)	Tissue engineering	High chondrocyte viability (86 %) after 7-day culture; effective for printing anatomically shaped cartilage constructs.	86 % chondrocyte viability after 7 days	[85,90]
Nanocellulose + carbon nanotubes	3D-bioprinting	Improved neuroblastoma cell adhesion, differentiation, and proliferation; promising for cardiovascular applications.	Enhanced cell adhesion and differentiation with minimal impact on viability	[84,94]
Bamboo waste	Cosmetic	Demonstrates stability without creaming for 30 days across a pH range of 3.0 to 9.0 and temperatures from 4 °C to 50 °C.	Stability for 30 days; pH range 3.0-9.0; temperature range 4 °C-50 °C	[97]

lightweight composites. Nanocellulose has also been extracted from postconsumer cotton and blended fabrics to efficiently produce cellulose nanocrystals [105]. Silk fibers, specifically *Bombyx mori* and *Antheraea pernyi* silk, have been investigated for nanocellulose production [106]. The resulting nanofibers and silk fibroin scaffolds exhibit excellent mechanical properties and have potential applications in cell proliferation and tissue engineering [107]. The isolation of cellulose nanofibrils from coconut waste to produce sewing thread also has been investigated [108,109]. Nanocellulose introduces a new dimension to textiles and apparel with its moisture management properties and flexibility [110]. Its ability to efficiently wick moisture away from the body enhances comfort, making it suitable for sportswear and activewear. The material's inherent flexibility allows for the creation of soft and comfortable fabrics, while its durability ensures that clothing items maintain their quality and performance over time [111].

Nanocellulose exhibits properties such as easy care, low impurity, good mechanical strength, and biocompatibility, making it suitable for various applications. It has found significant use in the antimicrobial medical field and paste printing. In the context of antibacterial applications, CNFs infused with pomegranate-AuNPs stand out as a stable and non-cytotoxic material, demonstrating remarkable effectiveness against bacteria. This is evident through a substantial reduction, ranging from 60 % to 99 %, in bacterial colonies [112]. Owing to its molecular configuration and expansive active surface area, nanocellulose holds significant relevance in the textile sector for medical purposes, presenting attributes like antistatic properties, minimal impurities, and exceptional mechanical and liquid absorption capabilities [110,113]. Modifying the surface of cellulose fibers is deemed as an efficient method to attain antimicrobial functionality. Notably, cellulose treated with methylol-5, 5-dimethylhydantoin leads to the formation of chloramines on the fiber surface, thereby conferring antimicrobial properties [114].

In the filed of easy-care textiles, nanocellulose plays a crucial role in the cross-linking of adjacent cellulose chains, creating fabrics with enhanced properties [115]. Cross-linking is achieved using various agents, with recent developments focusing on non-formaldehyde cross-linkers for environmental and health considerations. These cross-linkers, such as amide-glyoxal reactants, contribute to the easy-care properties of cellulosic blending[110].

2.3.2. Electromagnetic interference

The effective shielding of electronic devices operating in radio frequency bands remains a prominent concern, and nanocellulose derived from waste biomass emerges as a viable solution. Essential for safeguarding sensitive circuits and shielding workspaces from radiations emitted by computers and telecommunication equipment, lightweight electromagnetic interference (EMI) shielding materials play a crucial role. Electromagnetic waves emitted by electronic devices can potentially have adverse effects on human health as they may be reflected or absorbed by the human body. Research suggests that nanocellulose papers and composites incorporating conductive polymers like polyaniline (PANI) can achieve impressive results, with over 99 % attenuation of microwave radiation in the X-band frequency range (8–12 GHz) and shielding effectiveness values surpassing −20 dB for a 1 mm thick material [116]. Moreover, nanocellulose derived from red mud industrial waste and multiwall carbon nanotubes demonstrated remarkable –83 dB shielding in the X-band [117]. The unique characteristics of nanocellulose, including its high aspect ratio and hydroxyl groups, facilitate the uniform coating of conductive polymers, establishing a continuous network that effectively reflects or absorbs EMI. These flexible and lightweight nanocellulose EMI shields exhibit comparable or superior performance to metal shields, with the added advantage of being sourced from sustainable waste materials through green chemistry. The data strongly emphasizes the potential of nanocellulose composites as efficient EMI shielding materials, offering an environmentally friendly alternative to traditional metals and addressing the growing imperative to mitigate electromagnetic pollution [118].

Table 4 provides a comprehensive summary of the uses of nanocellulose within the textiles sector.

2.4. Electronics

2.4.1. Optical film

Nanocellulose from wasted materials shows potential for electrochemical, electrical, and optical applications in the electronics industry (Fig. 9g). It can be modified to obtain unique properties, including chiral mesoporous materials. Nanocellulose also enhances the performance of lithium-ion batteries and enables various applications, such as chiral plasmonic and optical materials. Particularly, when used as a replacement for aluminum foil alongside carbon nanotubes, it has showcased a remarkable 17 % improvement in performance [119]. A notable objective in this realm involves the production of chiral nematic materials from cellulose nanocrystals, frequently in conjunction with other polymers or silica. This distinctive strategy enables the targeted

Table 4
Summary of nanocellulose applications in textiles.

Material source	Application	Key findings	Numerical results	Ref
Rice straw and banana stem	Fabric enhancement (cotton fabrics)	Improves mechanical properties, dye uptake, water absorbency, and air permeability.	–	[103,104]
Cotton waste	Nanocellulose-reinforced composites	Produces lightweight composites with enhanced properties.	–	[105]
Silk fibers (*Bombyx mori*, Antheraea pernyi)	Nanocellulose production and scaffolds	Results in excellent mechanical properties; potential for cell proliferation and tissue engineering.	–	[106,107]
Coconut waste	Sewing thread production	Nanocellulose from coconut waste used to produce sewing threads.	–	[109]
Pomegranate	Antibacterial applications	Effective against bacteria with a reduction of bacterial colonies ranging from 60 % to 99 %.	Reduction of 60 % to 99 % in bacterial colonies	[112]
Nanocellulose (with conductive polymers like polyaniline)	EMI shielding	Achieves over 99 % attenuation of microwave radiation in the X-band (8–12 GHz).	Shielding effectiveness > −20 dB for 1 mm thickness	[116]
Nanocellulose (derived from red mud industrial waste)	EMI shielding	Demonstrates exceptional shielding performance when combined with multiwall carbon nanotubes.	−83 dB shielding in the X-band	[117]

elimination of specific elements, culminating in the creation of chiral mesoporous substances with diverse applications spanning from chiral plasmonics to anti-reflective coatings [110]. Furthermore, a wide array of potential applications in the electronics sector include chiral plasmonics, responsive hydrogels, anti-reflective coatings, optical filters, adaptable electronics, and flexible actuators. Leveraging its distinct characteristics, nanocellulose has been utilized to design optical materials featuring surface plasmons, UV blockage, fluorescence, and materials with low refractive indices, thereby unlocking avenues for applications like greenhouse plastics, particle tracking technology, sensing mechanisms, and anti-counterfeiting measures [120,121]. The incorporation of nanocellulose as a reinforcing agent in polymer composites improves their mechanical properties and thermal conductivity. For example, silk-nano cellulose fibrous composites exhibit outstanding mechanical properties, rendering them suitable for applications in electronics [122]. Additionally, this study investigated the utilization of corn husks as a nanocellulose source, resulting in the production of highly transparent and hydrophobic nanocellulose films with properties well-suited for optical and electronic devices [123]. The incorporation of nanocellulose from oil palm empty fruit bunch into epoxy composites enhances their thermal conductivity, making them suitable for electronic applications [124]. Nanocellulose from waste materials can also be utilized to develop flexible and transparent conductive films for touch screens, solar cells, and electronic displays. The study emphasizes the outstanding mechanical and electrical properties of nanocellulose-based composites, suggesting their potential as replacements for conventional conductive materials [125]. The use of nanocellulose from waste materials in the electronics and electrical industry not only contributes to waste reduction but also offers sustainable solutions to produce advanced materials. Nanocellulose's attributes find applications in the electronics industry, particularly in the development of flexible and durable electronic components. Its thermal stability ensures that electronic devices can operate efficiently even in high-temperature environments [126]. Additionally, nanocellulose's electrical insulation properties make it an excellent choice for preventing electrical leakage and ensuring the safe operation of electronic devices [127].

Fluorescent carbon dots (C-dots) sourced from biowastes have emerged as a significant advancement in the domain, demonstrating remarkable fluorescence characteristics and compatibility with biological systems. The C-dots possess distinctive quantum confinement traits owing to their diminutive size, which enhances their extraordinary fluorescence. The importance of these fluorescent attributes is reflected in their wide-ranging applications, especially in bio-imaging and energy technologies. Their swift and straightforward synthesis utilizing eco-friendly chemical precursors has further propelled their use in various fields. Employing green precursors for C-dots not only tackles the issue of biomass disposal through scientific means but also paves the way for a circular economy. This strategy not only reduces biowaste but also taps into the potential of fluorescent C-dots to support sustainable practices in agriculture [121]. Fig. 14 depicts the detailed procedure involved in

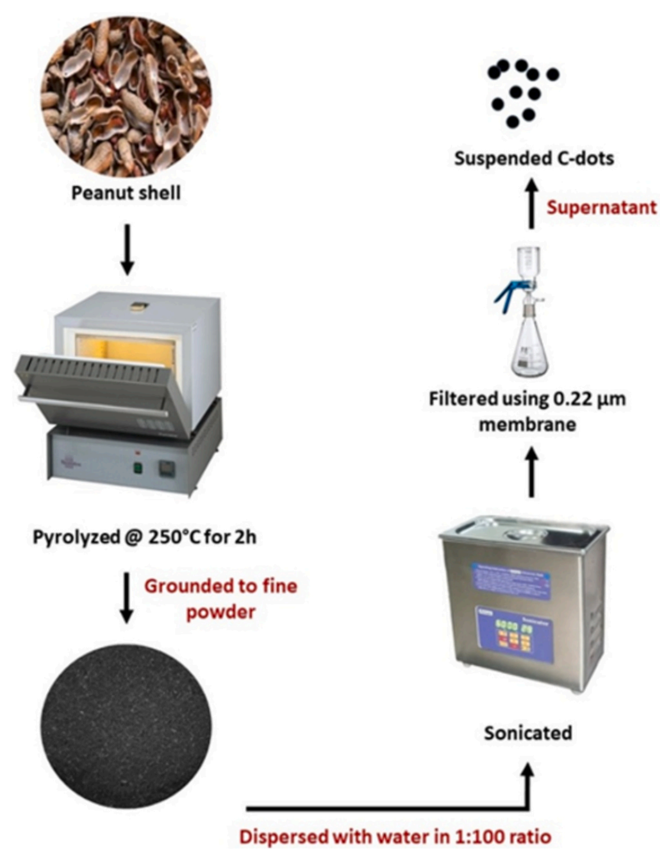

Fig. 14. C-dots from peanut shells [121].

the production of C-dots peanut shells.

C-dots, are naturally chemically and electrically conductive, making them ideal for use as electrodes in lithium and sodium-ion batteries. Semiconducting C-dots contribute to the enhanced stability of the surfaces of active electrode materials. Nitrogen self-doped C-dots, sourced from *Allium fistulosum*, have been explored as quantum dot sensitizers in solar cells. Comprehensive research has shown how factors such as particle size, energy level configuration, doping elements, and the methods used to produce C-dots influence the photoelectric properties of these solar cells (Fig. 15) [121].

2.4.2. Biosensings

Biosensors, typically combining biological components like sweat or saliva with physicochemical detectors, can range from heavy machinery to portable wearable devices (Fig. 9h). Recently, there's been a surge in interest towards portable sensors due to their ease of use, portability, rapid diagnostics, and reduced need for sample preparation. This section explores the development of biosensors for health monitoring, diagnostics, spectrometry, and other applications [128]. NC-based platforms offer a cost-effective, disposable, and efficient solution for various biosensing applications including healthcare, environmental monitoring, and food quality control. The versatility of NC structures, whether as hydrogels or aerogels, allows for diverse configurations that cater to different sensing mechanisms such as colorimetric, photoluminescence, mechanical deformation, and electrical responses [129]. Moreover, the abundant nanocellulose nanoscale source, combined with its biocompatibility, renewability, and low cost, makes it a sustainable alternative to conventional sensing platforms. The future prospects for nanocellulose in biosensing applications, particularly in filaments, paper-based platforms, and gel-like sensing devices, are promising [130].

Electrochemical biosensors play a crucial role in transforming biochemical information into analytical signals, particularly through the detection of analyte concentrations based on measurable electrical responses. These sensors have been instrumental in detecting biomolecules like adenine and guanine, offering valuable insights into Deoxyribonucleic acid (DNA) sequencing, oxidative harm, and protein metabolism within cells. Recent progress has centered on fabricating thin layers comprising nanocellulose and single-walled carbon nanohorns (SWCNHs) for the precise and selective identification of adenine and guanine bases in Ribonucleic acid (RNA) and DNA [128]. These layers exhibit resistance to fouling and high catalytic efficacy, facilitating the detection of bases with a detection limit as low as 1.4×10^{-6} mol L^{-1} for adenine and 1.7×10^{-7} mol L^{-1} for guanine. Additionally, electrochemical biosensors have been developed for monitoring lactate levels in artificial sweat using nanocellulose-based substrates, showing promising results for health monitoring applications [128]. Wearable electrochemical biosensing devices, including rings [131], patches [132], wristbands [133], and tattoos [134], have been fabricated using conducting polymers and nanocellulose nanocomposites. These gadgets provide benefits such as user-friendly operation, portability, and minimal sample preparation requisites, rendering them suitable for continual health monitoring. Another noteworthy advancement involves the creation of a sensitive enzymatic cholesterol biosensor utilizing PANi/CNC/IL nanocomposites, showcasing exceptional reproducibility, durability, and operational consistency in measuring cholesterol levels for food industries and clinical diagnostics [135].

2.4.3. Dielectric glass

The exploration of waste-derived nanocellulose in dielectric materials opens a new frontier in microelectronic devices. Investigating glass and glass-ceramics synthesized from agricultural waste ashes, such as sugarcane leaves ash and rice husk ash, reveals the nuanced influence of alkali metal oxides, impacting melting points through eutectic reactions [136]. Sugarcane leaves ash, with its intricate suppression of the cristobalite phase, contributes to materials with a notable dielectric permittivity range (9–40), facilitated by inherent porosity. The presence of the less ordered augite phase further enhances dielectric properties. Elemental analysis, encompassing *Si*, alkali and alkaline earth metals, *Cu*, *Zn*, *Fe*, and substantial aluminum, delves into intricate compositions. X-ray powder diffraction (XRD) patterns highlight amorphous and crystalline phases, offering opportunities for compositional tailoring [136,137]. Utilizing agro-food waste ashes for synthesizing glasses and glass ceramics demonstrates potential in various engineering and medical fields [138,139]. Analysis of dielectric properties reveals a decline in permittivity, loss factor, and conductivity with escalating rice bran content, attributable to fewer mobile carriers [140]. The innate porosity of these materials diminishes thermal conductivity, dielectric permittivity, and density in comparison to conventionally produced glasses, while amplifying capabilities in sound wave sensing and absorption [138]. This characteristic positions them for integration into microelectronic tools such as band-pass filters, dielectric resonant antennas, and oscillators, necessitating dielectric permittivity values of ~10 or

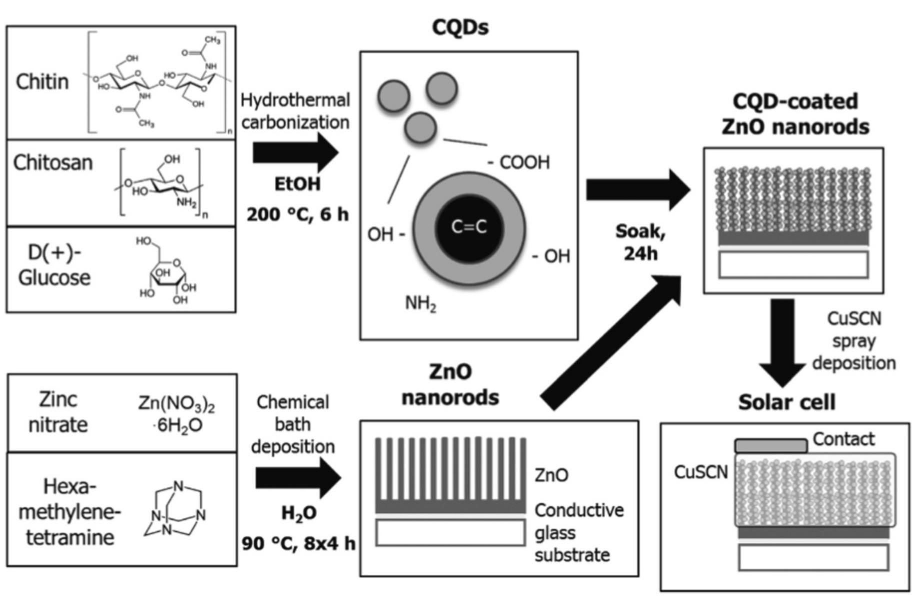

Fig. 15. A solar cell improved by incorporating C-dots [121].

higher, withstanding thermal and mechanical stress, and maintaining temperature and frequency independence within the microwave spectrum. Waste-derived substances like rice husk ash exhibit suitable dielectric constants for high-voltage utilities, while materials derived from mango shells, corncobs, rice husk, and bean shells find application in low-voltage scenarios. Furthermore, rice husk ash microwave absorbers, characterized by low bulk density, heightened electromagnetic wave absorption, and eco-friendliness, emerge as promising lightweight alternatives [141].

Table 5 presents an extensive overview of the applications of nanocellulose in the Electronics industry.

2.5. Other applications

2.5.1. Carbon capture

Mitigating CO_2 emissions is crucial in the fight against climate change, and advanced materials for CO_2 capture are vital for this endeavor (Fig. 9k). Nanocellulose, derived from waste sources, emerges as a promising candidate for CO_2 capture applications. Scientists are actively investigating diverse strategies, such as chemical modification and the inclusion of inorganic particles, to augment the adsorption capabilities of nanocellulose-based materials [142]. Functionalized nanocellulose aerogels, produced through physical or chemical cross-linking, have demonstrated potential for selective CO_2 capture [143]. Silane modifications, such as 3-aminopropylmethyldiethoxysilane, have been applied to nanocellulose aerogels, promoting CO_2 chemisorption [144]. Physisorption-based CO_2 sequestration has furthermore been successfully demonstrated through the utilization of aerogels composed of fibrillated nanocellulose impregnated with acetate-functionalized crystalline nanocellulose suspension [145]. These advancements highlight the versatility of waste-derived nanocellulose in creating efficient and selective CO_2 adsorbents [146]. Focusing on the utilization of lightweight and flexible cellulose nanofiber aerogels featuring monolithic structures is a captivating approach for CO_2 adsorption. The incorporation of cellulose acetate or acetylated cellulose nanocrystals as functional materials demonstrated promising CO_2 affinity. Investigations into the microstructure, mechanical characteristics, and behavior of CO_2 adsorption were conducted in a methodical manner, revealing remarkable mechanical strength alongside a significant CO_2 adsorption capability reaching 1.14 mmol/g at 101 kPa and 273 K. The incorporation of acetylated cellulose nanocrystals via impregnation resulted in a substantial improvement in both CO_2 adsorption capacity and axial mechanical attributes. This highlights the potential of nanocellulose-based materials in offering efficient and environmentally friendly solutions for CO_2 capture. Beyond its role as a CO_2 adsorbent, the study introduced an innovative impregnation process for attaching functional materials to aerogels, presenting new possibilities for diverse applications [147].

2.5.2. Wastewater treatment

Wastewater treatment presents a challenge, and waste-derived nanocellulose emerges as a versatile solution (Fig. 9l). Nanocellulose, abundant in hydroxyl groups, demonstrates efficacy in adsorbing heavy metals and organic compounds from contaminated water [148]. Various modifications, such as the integration of graphene oxide-silica and polypyrrole, enhance nanocellulose's affinity for pollutants like dyes [149]. Additionally, nanocellulose acts as an efficient filtering membrane for microorganisms and pollutants, showcasing its multifaceted role in water purification [148,150]. The incorporation of magnetic nanoparticles into nanocellulose further facilitates the separation of metals under an external magnetic field [151]. Chemical modifications, including sulfonation and amination, improve nanocellulose's hazardous metal retention, emphasizing its potential to address environmental challenges [152]. However, challenges such as limited removal capacity

Table 5
Summary of nanocellulose applications in electronics.

Material source	Application	Key findings	Numerical results	Ref
Nanocellulose (with carbon nanotubes)	Lithium-ion batteries, electronics	Improvement in battery performance and electronic applications; effective replacement for aluminum foil.	17 % performance improvement	[119]
Cellulose nanocrystals (with polymers or silica)	Chiral mesoporous materials	Enables creation of chiral nematic materials for diverse applications including chiral plasmonics.	–	[110]
Nanocellulose-based optical materials	Chiral Plasmonics, anti-reflective coatings	Applications in UV blockage, fluorescence, low refractive indices for greenhouse plastics and sensing.	–	[120]
Silk-nanocellulose fibrous composites	Electronics	Outstanding mechanical properties for electronic applications.	–	[122]
Nanocellulose from corn husks	Optical devices, transparent films	Production of highly transparent and hydrophobic films for optical and electronic applications.	–	[123]
Nanocellulose from oil palm empty fruit bunch	Epoxy composites, electronics	Enhanced thermal conductivity for improved performance in electronic applications.	–	[124]
Anocellulose + single-walled carbon nanohorns (SWCNHs)	Electrochemical biosensors	Enables precise detection of adenine and guanine in RNA and DNA; high catalytic efficacy and resistance to fouling.	Detection limit: 1.4×10^{-6} mol L^{-1} (adenine); 1.7×10^{-7} mol L^{-1} (guanine)	[128]
Nanocellulose + conducting polymers	Wearable electrochemical biosensors	Fabricated into rings, patches, wristbands, and tattoos; offers user-friendly operation, portability, and minimal sample preparation.	–	[130,131,133]
PANi/CNC/IL nanocomposites	Enzymatic cholesterol biosensors	High reproducibility, durability, and operational consistency for cholesterol measurement; suitable for food industries and clinical diagnostics.	–	[135]
Glass and glass-ceramics from agricultural waste ashes	Dielectric materials, microelectronics	Synthesized from sugarcane leaves ash and rice husk ash; influenced by alkali metal oxides and eutectic reactions. Sugarcane leaves ash shows a dielectric permittivity range of 9-40 due to porosity and phases like augite.	Dielectric permittivity range: 9-40	[137]
Sugarcane leaves ash	Dielectric materials	Suppresses cristobalite phase, contributing to high dielectric permittivity; presence of augite phase enhances properties.	–	[136]
Rice husk ash	Dielectric materials, microwave absorbers	Shows a decline in permittivity, loss factor, and conductivity with increased rice bran content; characterized by low bulk density and high electromagnetic wave absorption.	Dielectric permittivity: ~10 or higher	[140]
Agro-food waste ashes (various types)	Engineering and medical fields	Potential applications in high-voltage and low-voltage scenarios; suitability for microelectronic tools like band-pass filters, dielectric resonant antennas, and oscillators.	–	[138]
Rice husk ash (microwave absorbers)	Microwave absorption, lightweight alternatives	Low bulk density, high electromagnetic wave absorption, and eco-friendly; suited for lightweight dielectric applications.	–	[141]

compared to traditional adsorbents necessitate further research using real wastewater for scaling up laboratory assays.

Cellulose, particularly CNC, derived from sustainable resources, has garnered attention for wastewater treatment. CNC's large surface area, hydroxyl, and anionic sulfate ester groups make it an ideal substrate for composite materials. A recent study introduced a green aerogel composed of cellulose nanofibril and graphene oxide-silica, exhibiting exceptional efficiency in removing organic dyes from contaminated water. The composite aerogels displayed superior adsorption performances compared to pure cellulose nanofibril aerogels, showcasing a maximum adsorption capacity of 608.4 mg/g for methylene blue. This environmentally friendly aerogel, easy to fabricate and biodegradable, holds promise as an alternative for wastewater treatment [149]. Another study focused on sustainable cellulose nanofibril-based aerogels coated with polydopamine and cross-linked with polyethylenimine. These aerogels demonstrated robust porous structures with high porosity and low density, achieving significant adsorption capacities for contaminants like Cu (II) and methyl orange. The potential of cellulose nanomaterials in environmental remediation and water filtration technologies is highlighted, emphasizing their sustainable and efficient use [153,154].

Table 6 provides a comprehensive and detailed examination of the various applications and uses of nanocellulose within the contexts of both the Carbon Capture industry as well as the Wastewater Treatment sector, highlighting its significant potential and versatility in addressing environmental challenges.

To ensure clarity and comprehensibility, Table 7 has been devised to categorize and compare results obtained from a range of diverse waste materials. This table offers a comprehensive analysis of critical material attributes essential for selection in four distinct application domains: packaging, biomedical, textiles and apparel, and electronics. It is important to note that a comprehensive grasp of multiple parameters is required to delve into the potential utility of each material, facilitating meaningful comparisons and conclusive insights. The assessment of these attributes spans across different waste materials to ascertain their appropriateness for each specific application.

3. Material characteristics and attributes

Characteristics such as the modulus of elasticity [171], tensile strength [172], density [173], crystallinity [174], and thermal stability [175] are regarded as fundamental properties that play pivotal roles across a plethora of industries. These properties furnish vital information for material selection, design, and performance optimization in fields such as engineering, manufacturing, and biomedical applications.

Table 7
Key material attributes for various applications.

Material attribute	Packaging	Biomedical	Textiles and apparel	Electronics
Biodegradability	✓ [155]	✓ [156]	✓ [157]	✓ [158]
Mechanical strength	✓ [159]	✓ [160]	✓ [157]	✓ [161]
Durability	✓ [155]	✓ [162]	✓ [157]	✓ [161]
Thermal stability		✓ [162]	✓ [157]	✓ [163]
Resistance to moisture	✓ [164]			
Moisture management			✓ [165]	✓ [166]
Biocompatibility		✓ [167]		
Compatibility		✓ [168]	✓ [157]	
Chemical stability		✓ [163]		✓ [167]
Thermal conductivity				✓ [169]
Flexibility			✓ [157]	
Electrical insulation				✓ [170]

Nanocellulose's high modulus of elasticity and tensile strength make it suitable for applications that require strong and rigid materials. These properties contribute to its use as a reinforcing agent in composite materials, such as polymer composites or nanocellulose-reinforced materials. Nanocellulose's ability to enhance the mechanical properties of the host material makes it valuable in industries such as automotive, aerospace, and construction, where lightweight but robust materials are essential.

Nanocellulose's low density makes it attractive for lightweight applications. Its lightweight nature makes it suitable for applications where weight reduction is critical, such as in aerospace components or lightweight packaging materials. Additionally, its low density allows for improved material compactness, making it valuable in applications that require efficient use of space or flotation properties [176]. Highly crystalline nanocellulose exhibits enhanced strength and stiffness, making it suitable for applications that require high mechanical performance. This property is particularly beneficial in areas such as structural composites, films, coatings, and 3D-printed materials, where superior strength and rigidity are desired [177]. Nanocellulose's thermal stability is crucial for applications in high-temperature environments. Its ability to withstand thermal degradation without significant changes in its physical and chemical properties makes it suitable for applications such as flame-retardant materials, electronic components, and thermal insulation. Nanocellulose's thermal stability ensures that it can maintain its structural integrity and performance even under extreme heat

Table 6
Summary of nanocellulose applications in carbon capture and wastewater treatment.

Material source	Application	Key findings	Numerical results	Ref
Nanocellulose aerogels	CO_2 capture	Functionalized aerogels through cross-linking have potential for selective CO_2 capture.	–	[143]
Silane-modified nanocellulose aerogels	CO_2 chemisorption	Silane modifications (e.g., 3-aminopropylmethyldiethoxy-silane) enhance CO_2 chemisorption.	–	[144]
Fibrillated nanocellulose impregnated with acetate-functionalized crystalline nanocellulose	Physisorption-based CO_2 sequestration	Aerogels with acetate-functionalized crystalline nanocellulose show effective physisorption of CO_2.	–	[145]
Cellulose nanofiber aerogels with cellulose acetate or acetylated cellulose nanocrystals	CO_2 capture	High CO_2 adsorption capability with significant improvement in mechanical strength.	CO_2 adsorption capacity: 1.14 mmol/g at 101 kPa and 273 K	[147]
Nanocellulose with magnetic nanoparticles	Separation of metals using magnetic fields	Facilitates metal separation under an external magnetic field.	–	[151]
Nanocellulose with sulfonation and amination	Hazardous metal retention	Improved retention of hazardous metals through chemical modifications.	–	[152]
Green aerogel composed of cellulose nanofibril and graphene oxide-silica	Removal of organic dyes	Exceptional efficiency in removing dyes; superior to pure cellulose nanofibril aerogels.	Maximum adsorption capacity: 608.4 mg/g for methylene blue	[149]
Cellulose nanofibril-based aerogels coated with polydopamine and cross-linked with polyethylenimine	Water filtration and adsorption of contaminants	Robust porous structures with high porosity; effective for contaminants like cu (II) and methyl orange.	–	[154]

conditions [175].

Understanding and considering these characteristics is vital for material selection, design, and performance optimization across various industries. The combination of these properties determines the suitability of materials for specific applications, ensuring they meet the required performance, durability, and environmental conditions.

Table 8 highlights the specific material attributes required for each application area, offering valuable insights into the suitability of various waste materials based on their intrinsic properties. This detailed analysis offers a nuanced understanding of how specific properties directly or indirectly influence material suitability for distinct industries, guiding informed decision-making in material selection. The data elucidate that mechanical strength, a fundamental property, is directly correlated with both modulus of elasticity and tensile strength. This emphasizes the significance of these mechanical attributes in applications demanding structural integrity and load-bearing capacity. Conversely, density exhibits an inverse relationship with mechanical strength and durability, implying that materials with higher density may not be optimal for applications requiring robustness and long-termresilience.

Furthermore, Table 8 unveils the intricate interplay between specialized attributes and material properties. Notably, crystallinity directly affects thermal stability and insulation and insulating properties. This insight holds paramount importance in industries like construction and electronics, where efficient heat management is critical. Additionally, the direct relationship between biocompatibility and tensile strength highlights the relevance of these attributes in biomedical applications, where compatibility with biological systems and mechanical strength are pivotal considerations.

3.1. Raw materials from waste resources selected

Fig. 16 illustrates the varieties of waste materials employed in the production of nanocellulose. Fig. 17 provides a comprehensive scholarly exposition on nanocellulose sourcing, emphasizing the integral role of waste materials in sustainable nanomaterial production. Parameters, including cellulose content, hemicellulose, lignin percentages, diameter ranges, and crystallinity levels, offer indispensable insights into the nuanced properties of nanocellulose from various waste streams, such as wood, textile, paper, agricultural, and food waste. Comprehending the intricate interplay of cellulose, hemicellulose, and lignin is essential, as these components constitute the foundational elements of plant cell walls. Cellulose, a linear glucose polymer, forms crystalline microfibrils, bestowing mechanical strength [192]. Hemicellulose, a diverse sugar monomer-laden polymer, interconnects with cellulose, imparting flexibility [193]. Lignin, a complex phenolic polymer, acts as a binding matrix, providing rigidity and resistance to microbial degradation [194].

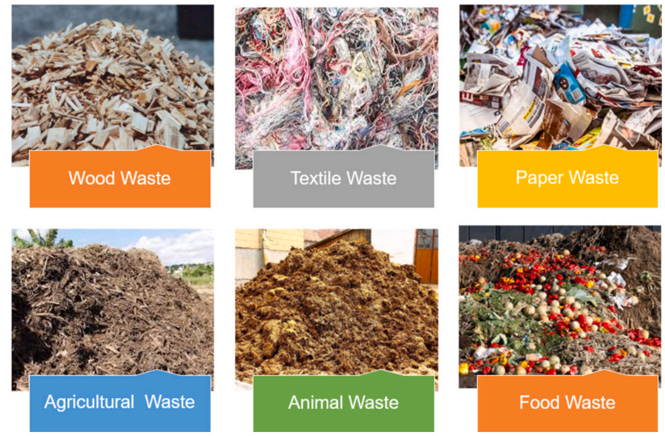

Fig. 16. Waste material diversity in Nanocellulose production.

In the realm of textile waste, a treasure trove of versatile materials awaits exploration. Cotton, celebrated for its softness and breathability, stands as a pillar in the textile industry. Textile waste stemming from cotton presents an opportunity for eco-conscious innovation. Similarly, the allure of silk, known for its luxurious sheen and lightweight properties, is a promising avenue for sustainable textiles and advanced materials. The exotic allure of *Antheraea pernyi* silk fibers, produced by the Ailanthus silkmoth, presents a unique source for specialty textiles and medical applications, warranting in-depth exploration. Wool, originating from sheep, offers natural warmth and insulating properties, making it a valuable resource in textiles, insulation, and beyond.

Within the realm of paper waste, materials with latent potential are discovered. Cardboard, with its robust and versatile nature, is identified as a prime candidate for recycling into new paper products or for conversion into innovative materials. Office paper, a ubiquitous presence in offices worldwide, is recognized for its significant recycling potential, thus contributing to sustainable paper production. Flax fibers, often overlooked in the paper industry, are found to contain cellulose and lignin, opening up possibilities for nanocellulose extraction or the creation of novel composite materials.

Agricultural waste is a rich source of sustainable materials with numerous applications. Sugarcane bagasse, a byproduct of sugar production, is abundant in cellulose and fibers, ideal for paper, composites, or nanocellulose production. Pineapple leaf, usually discarded, offers natural fibers suitable for textiles, composites, or nanocellulose. Wheat straw, a staple in agriculture, contains cellulose and lignin, making it suitable for nanocellulose, biofuels, or paper. Corn stover, often left

Table 8
Relationships between material characteristics and attributes.

	Modulus of elasticity	Tensile strength	Density	Crystallinity	Thermal stability	Ref
Mechanical strength	+	+	–	+		[178–180]
Chemical stability					+	[181]
Thermal stability				+	+	[181]
Thermal insulation	+			+	+	[182,183]
Biodegradability			–			[184]
Biocompatibility		+				[185]
Moisture management			–			[186]
Resistance to moisture			+			[187]
Durability			–			[187]
Insulating properties			+	+	+	[183,188,189]
Electrical conductivity				+		[190]
Flexibility	–	+				[182]
Thermal conductivity				–		[191]

In this combined table:
(+) indicates a direct relationship, meaning that the attribute is positively correlated with the application.
(-) indicates an inverse relationship, meaning that the attribute is negatively correlated with the application.
( ) indicates no direct relationship between the attribute and the application.

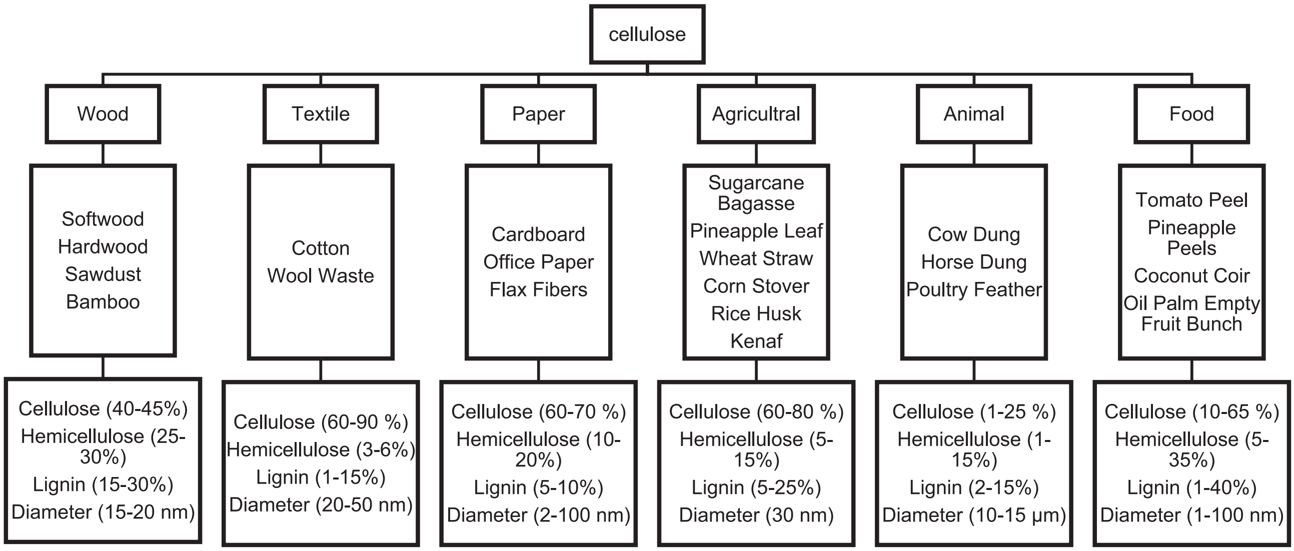

Fig. 17. Comparative analysis: cellulose content, and morphology of nanocellulose from diverse waste materials [14,15,195–198].

unutilized, contains cellulose-rich components suitable for nanocellulose, biofuels, or animal bedding. Rice husks, typically discarded, offer potential for nanocellulose production and can serve as a source of bioenergy. Kenaf hemp, an underutilized crop, possesses natural fibers and cellulose, suitable for textiles, composites, and potentially nanocellulose extraction. These agricultural waste materials showcase a sustainable path towards resource optimization and innovation.

Within the category of wood waste, a multitude of possibilities awaits exploration. Softwood, derived from trees like pine and spruce, boasts a lightweight yet robust nature. It's sought after in construction and woodworking, and its waste material can be repurposed for a myriad of applications, including nanocellulose production. Hardwood, represented by species like oak, maple, and birch, is celebrated for its durability and elegance. The waste from hardwood sources presents opportunities in high-quality furniture, flooring, and potential nanocellulose extraction. Sawdust, a byproduct of wood processing, may seem inconsequential but holds great value. It can be utilized in the manufacturing of particleboard, wood pellets, or as an absorbent material. Bamboo, a rapidly renewable resource, is sustainable and versatile, finding applications in textiles, construction, and potentially as a source of nanocellulose.

4. Examining the outcomes by the material specifications

Table 9 offers a comprehensive overview of nanocellulose characteristics sourced from diverse waste materials, including wood, textile, paper, agricultural, animal, and food waste. This data is pivotal for understanding nanocellulose's unique properties across different waste streams, guiding its application in textiles, composites, biofuels, and more. By showcasing the intricacies of nanocellulose from various sources, Table 9 emphasizes the importance of waste repurposing in fostering sustainable solutions and innovative materials. It serves as a vital resource for informed decision-making, promoting eco-conscious innovation, and contributing significantly to environmental conservation and resource optimization endeavors.

Table 9
Material characteristics of nanocellulose synthesized from waste materials.

Waste material		Modulus of elasticity (GPa)	Tensile strength (MPa)	Density (kg/m^3)	Crystallinity (%)	Thermal stability (°C)	Ref
Wood	Softwood	13	223	1600	55-90	345-370	[199–203]
	Hardwood	13-23.9	224-383	1550-1650	52-69	210-350	[155,204,205]
	Sawdust	0.157	–	600	70-90	250–400	[206,207]
	Bamboo	13-15	250-270	1500-1550	70-75	200-300	[208–210]
Textile	Cotton	2.04-2.71	30-50	1500	80-82	180–300	[211–214]
	Wool waste	0.01-0.15	31.78	–	54–88	280-370	[215,216]
Paper	Cardboard	27-30	2.6	1400	>70	250-400	[207,217]
	Office paper	1–15	–	1500-1600	>70	250-320	[207,218,219]
	Flax Fibers	21	70-75	1400	62-75	200-300	[217,220]
Agricultural	Sugarcane bagasse	17.00	290	1250	62-76	300-375	[221–224]
	Pineapple leaf	15-53	170-413	1450-1550	70-75	270-435	[225–228]
	Wheat straw	11.45	40-45	1550	70-80	310–360	[213,214,229,230]
	Corn stover	1-2.1	45-75	1550	45-75	–	[213,231–233]
	Rice husk	–	55-65	1550	–	378-488	[213,234]
	Kenaf	5-13	60-65	1600	60-80	352–358	[24,214,235,236]
Animal	Cow dung	11-17	25-35	518	47.6-53.3	200-400	[213,237,238]
	Horse dung	7-8	45-91	1400-1440	–	250-300	[239]
	Poultry feather	1.6 – 2.1	10- 18	1300-1500	–	300-400	[240,241]
Food	Tomato peel	18–50	–		75-90	280-350	[242–244]
	Pineapple peels	16-27.25	75-78	1400	65-85	220-295	[245–248]
	Coconut coir	4-9	54-250	1150-1450	50-75	300-340	[249,250]
	Oil palm empty fruit bunch	12-18	107–137	1600	85-90	300-400	[251–253]

4.1. Modulus of elasticity

The modulus of elasticity is a crucial mechanical property that characterizes the stiffness and elasticity of materials. In the context of nanocellulose, this property is particularly noteworthy due to the material's unique structure. Nanocellulose, derived from cellulose fibers, possesses a highly organized and crystalline structure at the nanoscale. This organized arrangement contributes to its exceptional modulus of elasticity, indicating a high level of stiffness and strength.

The modulus of elasticity varies significantly among different waste materials, highlighting their diverse mechanical properties. Materials like softwood, hardwood, and bamboo exhibit relatively high moduli of elasticity, ranging from 13 to 27 GPa. These materials are characterized by their stiffness and ability to return to their original shape after deformation. Softwood, including pine, spruce, and fir, is well-suited for structural applications in construction due to its rigidity. Bamboo, with its balance of strength and flexibility, finds applications in electronics and potentially as a source of nanocellulose for electronic devices, where mechanical strength is essential.

Cotton waste, with a modulus of elasticity ranging from 2.04 to 2.71 GPa, offers flexibility and lightweight properties[104]. This makes it valuable in textile and apparel applications, where pliability and comfort are desired. Wool, with a modulus ranging from 0.01 to 0.15 GPa, offers natural warmth and insulation, contributing to its use in textiles [215].

Some waste materials, such as sawdust, have low moduli of elasticity (0.157 GPa) and are not typically used for structural purposes [206] instead, sawdust can find value in applications like particleboard and wood pellets, where stiffness is not a primary requirement.

Overall, a thorough understanding of these material properties is crucial for determining their applicability in specific areas, such as structural materials, textiles, and composites used in packaging, biomedical devices, textiles, and electronic applications. Each material's unique modulus of elasticity contributes to its suitability for various industries and innovative uses.

4.2. Tensile strength

Tensile strength, a critical mechanical strength attribute measuring a material's resistance to stretching or breaking under tension, showcases the diverse suitability of different waste materials for various applications. Nanocellulose's exceptional tensile strength is intricately linked to its organized structure and the robust hydrogen bonding network within its composition. The organized structure of nanocellulose, with crystalline regions aligned along the cellulose chain, contributes to its remarkable tensile strength. The individual cellulose chains are held together by strong intra- and intermolecular hydrogen bonds, creating a highly cohesive and resilient material [254].

In addition to its structural organization, the abundance of hydrogen bonds in nanocellulose significantly contributes to its tensile strength. The dense network of hydrogen bonds provides effective load-bearing capabilities by distributing stress throughout the material. This structural reinforcement leads to enhanced mechanical properties, including tensile strength [255].

A decrease in the fiber diameter leads to an increase in tensile strength. This rise in strength is attributed to the conventional scaling law associated with smaller fiber diameters. Moreover, the simultaneous enhancement in toughness, measured through fracture toughness tests, suggests a self-healing mechanism facilitated by the breaking and reforming of hydrogen bonds during inter-fiber sliding. The interplay between nanocellulose's organized structure and the resilience of hydrogen bonds provides a foundation for its exceptional tensile strength, positioning it as a promising material for various applications [256].

Among hardwood varieties like oak, maple, and birch, an impressive tensile strength range of 224-383 MPa makes them top choices for load-bearing applications in construction and engineering due to their robustness [204]. Coconut coir emerges as a standout with its wide tensile strength range of 54-250 MPa [249]. This versatility allows for applications across industries, including textiles and composites, where varying strength requirements and biocompatibility are essential considerations. Conversely, cotton, with a tensile strength ranging from 30 to 50 MPa, aligns well with flexible and comfortable products such as textiles and apparel, addressing biocompatibility needs [213]. Nanocellulose demonstrates exceptional tensile strength ranging from several hundred to over a thousand megapascals (MPa). This remarkable mechanical strength, attributed to its organized structure and strong hydrogen bonding, positions nanocellulose as a highly valuable material for load-bearing applications across multiple sectors, including engineering, packaging, and biomedical devices. Moreover, agricultural waste materials like sugarcane bagasse and pineapple leaf display moderate to high tensile strength, opening various industrial applications [222,225]. However, materials like cow dung, characterized by a lower tensile strength of 25-35 MPa, may have limitations in load-bearing scenarios [213]. Recognizing and leveraging these variations is crucial for evaluating the appropriateness of waste materials for specific engineering and manufacturing purposes, particularly in the realms of packaging, biomedical devices, textiles, and electronic applications, where mechanical strength and biocompatibility play pivotal roles in material selection.

4.3. Density

The density of waste materials is a pivotal factor that influences their mechanical strength, biodegradability, moisture management, resistance to moisture, durability, insulating properties, and flexibility. Depending on the desired application, waste materials can be chosen strategically to optimize these properties and meet the specific requirements of packaging, biomedical, textile, and electronic applications.

In terms of mechanical strength, higher-density materials generally demonstrate greater resilience and resistance to deformation due to their closely packed molecular structure. This property makes them suitable for applications requiring robustness and durability, such as in structural components of buildings or machinery. Conversely, lower-density materials, with more loosely arranged molecules, may exhibit reduced mechanical strength and may find applications where flexibility or weight considerations are more critical than sheer strength [257].

Biodegradability is another property influenced by density. Higher density materials, characterized by tightly packed molecules, often resist biodegradation. The reduced accessibility of microorganisms to break down the material can result in longer persistence in the environment. In contrast, lower density materials, which are typically more porous, facilitate microbial access and, consequently, tend to be more biodegradable. This property is particularly important in the context of environmentally friendly materials and disposable products where biodegradability is a key consideration [258,259].

Density also plays a pivotal role in moisture-related properties of materials. Higher density materials, with their compact structure, often exhibit better resistance to moisture absorption. This characteristic is advantageous in applications where moisture management is crucial, such as in the construction industry or electronic devices. On the other hand, lower density materials, with increased porosity, may absorb moisture more readily, which can impact their performance, especially in humid or wet environments. The choice of material density is, therefore, a critical factor in designing products or structures with specific moisture-related requirements [260,261].

Materials with moderate densities, such as hardwood (1550-1650 kg/m^3) [262], and softwood (1600 kg/m^3) [202], strike a balance between mechanical strength and weight, making them suitable for load-bearing applications in packaging and construction. Their density contributes to their durability, while their moisture resistance ensures their longevity, a vital factor for packaging materials.

On the other hand, lightweight materials like sawdust (600 kg/m^3) [206]and cotton (1500 kg/m^3) [104] are more appropriate for textile applications due to their flexibility and moisture management properties. Cotton, with its density and flexibility, offers comfort in textile products, while its resistance to moisture helps maintain a dry and comfortable environment.

Biodegradable materials with varying densities, such as sugarcane bagasse (1250 kg/m^3) [222] and pineapple leaf (1450-1550 kg/m^3) [225], align well with sustainable practices in both packaging and biomedical applications. Their density impacts their moisture management capabilities, biodegradability, and overall environmental footprint, making them ideal choices for eco-conscious applications.

4.4. Crystallinity

Crystallinity, a crucial material property, significantly impacts the suitability of waste materials for various applications, including packaging, biomedical, textile, and electronic applications. It is closely related to several other attributes, making it a vital consideration in material selection. Materials such as softwood (55-90 %) [200] and hardwood (52-69 %) [205], often exhibit high mechanical strength, making them suitable for load-bearing applications in packaging. Their crystalline structure contributes to their rigidity and durability, which are essential for packaging materials. In contrast, materials, like cotton (80-82 %) [217] and bamboo (70-75 %) [263], are well-suited for textile applications due to their flexibility and comfort. Cotton, with its high thermal stability, offers strength and durability in textile products. In electronic applications, waste materials with controlled crystallinity, like coconut coir (50-75 %) [249], can be advantageous. Their ability to manage thermal insulation and electrical and thermal conductivity makes them suitable for certain electronic devices.

Crystallinity plays a crucial role in determining the suitability of materials for biomedical applications, particularly in the development of scaffolds for tissue engineering and drug delivery systems. Biomedical applications benefit from materials with moderate crystallinity, such as sugarcane bagasse (62-76 %) [223] and pineapple leaf (70-75 %) [227]. Their crystalline structure aligns well with the thermal stability and insulation properties required in biomedical devices. This crystalline structure contributes to the material's ability to support cell adhesion, proliferation, and differentiation, which are fundamental processes in tissue regeneration [85]. Furthermore, the thermal stability associated with crystalline regions enhances the material's resistance to degradation during sterilization processes, a critical factor in maintaining the integrity of biomedical implants and devices [264].

The controlled crystallinity of waste materials also influences their potential as drug delivery vehicles. The presence of both crystalline and amorphous regions in materials like sugarcane bagasse and oil palm empty fruit bunch allows for the efficient encapsulation and controlled release of therapeutic agents [73]. The crystalline domains provide structural stability and can modulate the release kinetics of drugs, while the amorphous regions facilitate drug loading and biodegradation. Additionally, the inherent biocompatibility of these plant-based materials, coupled with their crystalline structure, reduces the risk of adverse immune responses when used in vivo [265].This combination of properties makes waste materials with moderate crystallinity promising candidates for developing sustainable and effective biomedical solutions, from wound dressings to drug-eluting implants.

4.5. Thermal stability

Thermal stability is closely tied to other properties, making it a crucial consideration in material selection. Materials with high thermal stability, such as rice husk (378-488 °C) [234] and oil palm empty fruit bunch (300-400 °C) [249], are well-suited for high-temperature applications like fire-resistant coatings or insulation. Their ability to withstand significant heat without degradation makes them valuable in extreme environments. Nanocellulose, derived from waste materials, exhibits exceptional thermal stability, surpassing 200 °C. This is attributed to its robust bonds and compact structure, providing resistance against thermal decomposition.

The thermal stability of waste-derived nanocellulose can be attributed to the presence of strong intermolecular bonds, such as hydrogen bonds, within its molecular structure. These robust bonds play a crucial role in resisting thermal decomposition. Additionally, the nanocellulose's compact structure contributes to its thermal stability by limiting the movement of molecules and reducing the likelihood of bond breakage at elevated temperatures. The organized and closely packed arrangement of cellulose chains in the nanocellulose structure enhances its overall resistance against thermal degradation, making it a promising material for applications where thermal stability is a critical factor [266,267].

This makes nanocellulose a valuable material for applications like flame-retardant coatings, thermal insulation, and reinforcing polymer composites. In contrast, materials with moderate thermal stability, like sugarcane bagasse (300-375 °C) [224] and pineapple leaf (270-435 °C) [228], offer sufficient resistance to heat for applications in biocomposites, packaging, and insulation. These materials strike a balance between thermal stability and processability. Materials with lower thermal stability, such as cotton (180-300 °C) [212] and bamboo (200-300 °C) [209], are more suitable for applications where heat resistance is not the primary requirement, such as textiles and certain packaging materials. Overall, the thermal stability of waste materials plays a vital role in determining their suitability for specific applications. Waste materials can be strategically selected based on their thermal stability to optimize their performance in packaging, biomedical, textile, and electronic applications.

5. Comparison of nanocellulose with other biopolymers

To provide a comprehensive understanding of the mechanical properties of nanocellulose, the modulus of elasticity, tensile strength, density, crystallinity, and thermal stability of nanocellulose were compared with those of other biopolymers, such as chitosan, starch, polylactic acid (PLA), and polyhydroxyalkanoates (PHA). These comparisons were drawn from the results presented in the discussion of waste-derived materials, illustrating the unique advantages and potential applications of nanocellulose in contrast to these other biopolymers. These results are summarized in Table 10.

Nanocellulose emerges as the most versatile biopolymer, exhibiting a wide range of modulus of elasticity. This allows its stiffness to be tailored to match various application requirements, from rigid packaging to flexible electronics. In contrast, chitosan is relatively stiff, while starch and PHA are more compliant.

Nanocellulose demonstrates exceptional tensile strength, ranging from several hundred MPa, far exceeding that of other biopolymers. This remarkable strength enables nanocellulose to withstand substantial loads and stresses, making it ideal for high-performance applications like structural components and protective packaging. Chitosan, starch, and PHA exhibit lower tensile strengths, typically below 100 MPa, positioning them for less demanding applications. PLA maintains a consistent tensile strength of 50-70 MPa, suitable for moderate-strength requirements.

Nanocellulose, chitosan, and starch have similar densities. The high crystallinity of nanocellulose, ranging from 55 % to 90 %, contributes to its superior mechanical properties and stability. In contrast, chitosan, starch, and PLA have lower crystallinity, indicating a more amorphous structure and potentially different processing requirements and end-use characteristics.

Nanocellulose and chitosan demonstrate comparable thermal stability, exceeding 200 °C, making them suitable for high-temperature applications such as insulation and coatings. Starch exhibits the

Table 10
Property comparison of nanocellulose and other biopolymers.

Biopolymers	Modulus of elasticity (GPa)	Tensile strength (MPa)	Density (kg/m^3)	Crystallinity (%)	Thermal stability (°C)	Ref
Nanocellulose	1-50	1-400	1300-1600	55-90	≥200	
Chitosan	13-23.9 100 g/denier	20–100 (dry) 17.5 (wet) 4 g/denier	1350-1550	35-50	~200	[268,269]
Starch	1-3	1-50	1300-1500	20-40	200–250	[270–272]
PLA	2-16	50-70	1200-1300	35-70	150-200	[273,274]
PHA	1-2	15-40	–	40-60	160–175	[275]

highest thermal stability, while PLA and PHA are less thermally resistant. The thermal stability of these biopolymers is a crucial factor in determining their suitability for processing and end-use environments.

The diverse properties of these biopolymers offer a wide range of possibilities for selective material choice and application development. Nanocellulose stands out with its exceptional mechanical strength, stiffness, and thermal stability, positioning it as a highly versatile and high-performance biomaterial. The other biopolymers, while exhibiting distinct characteristics, can also be strategically utilized in applications where their specific attributes, such as flexibility, biodegradability, or moderate thermal resistance, are advantageous.

6. Conclusions

The diverse mechanical properties of waste-derived materials play a pivotal role in determining their suitability across various industries. For instance, softwoods such as pine, spruce, and fir exhibit a modulus of elasticity ranging from 13 to 27 GPa, making them ideal for applications requiring structural rigidity, such as load-bearing packaging materials. In contrast, cotton, with a modulus ranging from 2.04 to 2.71 GPa, offers flexibility and reduced weight, making it valuable in scenarios where lightweight and pliable materials are needed. When it comes to tensile strength, hardwoods like oak, maple, and birch showcase strengths ranging from 224 to 383 MPa, excelling in load-bearing applications, while coconut coir, with a diverse range of 54 to 250 MPa, proves versatile in various engineering and manufacturing applications. Additionally, the moderate densities of hardwood and softwood ranging from 1550 to 1650 kg/m^3 strike a balance between mechanical strength and weight, making them well-suited for load-bearing applications in packaging and construction. Furthermore, the high crystallinity of softwood (55-90 %) and hardwood (52-69 %) materials correlates with their mechanical strength, rendering them suitable for load-bearing purposes, especially in packaging applications where durability is paramount. Lastly, materials like rice husk and oil palm empty fruit bunch exhibit thermal stability ranging from 300 to 488 °C, making them suitable for high-temperature applications such as fire-resistant coatings or insulation, while nanocellulose derived from waste materials also demonstrates exceptional thermal stability, expanding its potential applications in various heat-resistant products across industries. These nuanced mechanical, density, crystallinity, and thermal properties of waste-derived materials provide a comprehensive understanding of their potential applications, guiding sustainable innovation and material selection processes for eco-friendly product development and waste management practices.

CRediT authorship contribution statement

Mehrdad Ghamari: Writing – original draft, Methodology, Conceptualization. **Dongyang Sun:** Writing – review & editing, Validation. **Yanqi Dai:** Writing – review & editing. **Chan Hwang See:** Writing – review & editing, Investigation. **Hongnian Yu:** Writing – review & editing, Visualization. **Mohan Edirisinghe:** Validation, Investigation. **Senthilarasu Sundaram:** Visualization, Validation, Supervision, Investigation.

Declaration of competing interest

We declare that we wish to confirm the absence of any known conflicts of interest associated with this publication. Additionally, we affirm that there has been no significant financial support for this work that could have influenced its outcome.

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

References

[1] F.R. Dalby, S.D. Hafner, S.O. Petersen, A.C. VanderZaag, J. Habtewold, K. Dunfield, M.H. Chantigny, S.G. Sommer, Understanding methane emission from stored animal manure: a review to guide model development, J. Environ. Qual. 50 (2021) 817–835, https://doi.org/10.1002/jeq2.20252.
[2] S. Kaza, L.C. Yao, P. Bhada-Tata, F. Van Woerden, What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050, World Bank, Washington, DC, 2018, https://doi.org/10.1596/978-1-4648-1329-0.
[3] G. Blumberg, M. Sibilla, A carbon accounting and trading platform for the Uk construction industry, Energies (Basel) 16 (2023) 1566, https://doi.org/10.3390/en16041566.
[4] DEFRA, Nutr. Food Sci. 40 (2010), https://doi.org/10.1108/nfs.2010.01740eab.009.
[5] P. Morseletto, Targets for a circular economy, Resour. Conserv. Recycl. 153 (2020), https://doi.org/10.1016/j.resconrec.2019.104553.
[6] R.Y. Paquibut, M.C. Legion, A.R.M. Islam, I.S. Chaudhry, L. Gernal, Sustainable plastics waste management framework based on the analysis of people's awareness, knowledge, attitude, skills, and action: development of sustainable plastics waste management approaches, Int. J. Environ. Sci. Technol. 20 (2023) 10217–10228, https://doi.org/10.1007/s13762-022-04675-x.
[7] H. Seddiqi, E. Oliaei, H. Honarkar, J. Jin, L.C. Geonzon, R.G. Bacabac, J. Klein-Nulend, Cellulose and its derivatives: towards biomedical applications, Cellulose 28 (2021) 1893–1931, https://doi.org/10.1007/s10570-020-03674-w.
[8] S.H. Ghaffar, M. Burman, N. Braimah, Pathways to circular construction: an integrated management of construction and demolition waste for resource recovery, J. Clean. Prod. 244 (2020) 118710, https://doi.org/10.1016/j.jclepro.2019.118710.
[9] J. Kirchherr, N.-H.N. Yang, F. Schulze-Spüntrup, M.J. Heerink, K. Hartley, Conceptualizing the circular economy (revisited): an analysis of 221 definitions, Resour. Conserv. Recycl. 194 (2023) 107001, https://doi.org/10.1016/j.resconrec.2023.107001.
[10] A.N.S. Ahmad Khorairi, N.-S. Sofian-Seng, R. Othaman, H. Abdul Rahman, N. S. Mohd Razali, S.J. Lim, W.A. Wan Mustapha, A review on agro-industrial waste as cellulose and nanocellulose source and their potentials in food applications, Food Rev. Int. 39 (2023) 663–688, https://doi.org/10.1080/87559129.2021.1926478.
[11] T. Krexner, A. Bauer, W. Zollitsch, K. Weiland, A. Bismarck, A. Mautner, F. Medel-Jiménez, A. Gronauer, I. Kral, Environmental life cycle assessment of nanocellulose and biogas production from manure, J. Environ. Manag. 314 (2022) 115093, https://doi.org/10.1016/j.jenvman.2022.115093.
[12] K. Dhali, M. Ghasemlou, F. Daver, P. Cass, B. Adhikari, A review of nanocellulose as a new material towards environmental sustainability, Sci. Total Environ. 775 (2021) 145871, https://doi.org/10.1016/j.scitotenv.2021.145871.
[13] S. Mateo, S. Peinado, F. Morillas-Gutiérrez, M.D. La Rubia, A.J. Moya, Nanocellulose from agricultural wastes: products and applications—a review, Processes 9 (2021) 1594, https://doi.org/10.3390/pr9091594.
[14] D. Klemm, F. Kramer, S. Moritz, T. Lindström, M. Ankerfors, D. Gray, A. Dorris, Nanocelluloses: a new family of nature-based materials, Angew. Chem. Int. Ed. 50 (2011) 5438–5466, https://doi.org/10.1002/anie.201001273.
[15] V. Kumar, P. Pathak, N.K. Bhardwaj, Waste paper: an underutilized but promising source for nanocellulose mining, Waste Manag. 102 (2020) 281–303, https://doi.org/10.1016/j.wasman.2019.10.041.
[16] M. Rajinipriya, M. Nagalakshmaiah, M. Robert, S. Elkoun, Importance of agricultural and industrial waste in the field of nanocellulose and recent industrial developments of wood based nanocellulose: a review, ACS Sustain. Chem. Eng. 6 (2018) 2807–2828, https://doi.org/10.1021/acssuschemeng.7b03437.

[17] S. Kalia, A. Dufresne, B.M. Cherian, B.S. Kaith, L. Avérous, J. Njuguna, E. Nassiopoulos, Cellulose-based bio- and nanocomposites: a review, Int. J. Polym. Sci. 2011 (2011) 1–35, https://doi.org/10.1155/2011/837875.
[18] A.N.S. Ahmad Khorairi, N.-S. Sofian-Seng, R. Othaman, H. Abdul Rahman, N. S. Mohd Razali, S.J. Lim, W.A. Wan Mustapha, A review on agro-industrial waste as cellulose and nanocellulose source and their potentials in food applications, Food Rev. Int. 39 (2023) 663–688, https://doi.org/10.1080/87559129.2021.1926478.
[19] J. Dharmaraja, S. Shobana, S. Arvindnarayan, R.R. Francis, R.B. Jeyakumar, R. G. Saratale, V. Ashokkumar, S.K. Bhatia, V. Kumar, G. Kumar, Lignocellulosic biomass conversion via greener pretreatment methods towards biorefinery applications, Bioresour. Technol. 369 (2023) 128328, https://doi.org/10.1016/j.biortech.2022.128328.
[20] K. Dhali, M. Ghasemlou, F. Daver, P. Cass, B. Adhikari, A review of nanocellulose as a new material towards environmental sustainability, Sci. Total Environ. 775 (2021) 145871, https://doi.org/10.1016/j.scitotenv.2021.145871.
[21] S. Yu, J. Sun, Y. Shi, Q. Wang, J. Wu, J. Liu, Nanocellulose from various biomass wastes: its preparation and potential usages towards the high value-added products, Environ. Sci. Ecotechnol. 5 (2021) 100077, https://doi.org/10.1016/j.ese.2020.100077.
[22] X. Wang, C. Yao, F. Wang, Z. Li, Cellulose-based nanomaterials for energy applications, Small 13 (2017), https://doi.org/10.1002/smll.201702240.
[23] D. Klemm, F. Kramer, S. Moritz, T. Lindström, M. Ankerfors, D. Gray, A. Dorris, Nanocelluloses: a new family of nature-based materials, Angew. Chem. Int. Ed. 50 (2011) 5438–5466, https://doi.org/10.1002/anie.201001273.
[24] P. Phanthong, P. Reubroycharoen, X. Hao, G. Xu, A. Abudula, G. Guan, Nanocellulose: extraction and application, Carbon Res. Convers. 1 (2018) 32–43, https://doi.org/10.1016/j.crcon.2018.05.004.
[25] P.E. Lokhande, P.P. Singh, D.-V.N. Vo, D. Kumar, K. Balasubramanian, A. Mubayi, A. Srivastava, A. Sharma, Bacterial nanocellulose: green polymer materials for high performance energy storage applications, J. Environ. Chem. Eng. 10 (2022) 108176, https://doi.org/10.1016/j.jece.2022.108176.
[26] Z. Kassab, Y. Abdellaoui, M.H. Salim, R. Bouhfid, A.E.K. Qaiss, M. El Achaby, Micro- and nano-celluloses derived from hemp stalks and their effect as polymer reinforcing materials, Carbohydr. Polym. 245 (2020) 116506, https://doi.org/10.1016/j.carbpol.2020.116506.
[27] A. Sonia, K. Priya Dasan, Chemical, morphology and thermal evaluation of cellulose microfibers obtained from Hibiscus sabdariffa, Carbohydr. Polym. 92 (2013) 668–674, https://doi.org/10.1016/j.carbpol.2012.09.015.
[28] M. El Achaby, Z. Kassab, A. Aboulkas, C. Gaillard, A. Barakat, Reuse of red algae waste for the production of cellulose nanocrystals and its application in polymer nanocomposites, Int. J. Biol. Macromol. 106 (2018) 681–691, https://doi.org/10.1016/j.ijbiomac.2017.08.067.
[29] K.O. Reddy, C.U. Maheswari, M.S. Dhlamini, B.M. Mothudi, V.P. Kommula, J. Zhang, J. Zhang, A.V. Rajulu, Extraction and characterization of cellulose single fibers from native african napier grass, Carbohydr. Polym. 188 (2018) 85–91, https://doi.org/10.1016/j.carbpol.2018.01.110.
[30] L. Ravindran, S.M. S., S. Thomas, Novel processing parameters for the extraction of cellulose nanofibres (CNF) from environmentally benign pineapple leaf fibres (PALF): structure-property relationships, Int. J. Biol. Macromol. 131 (2019) 858–870, https://doi.org/10.1016/j.ijbiomac.2019.03.134.
[31] Z. Wang, Z. Yao, J. Zhou, Y. Zhang, Reuse of waste cotton cloth for the extraction of cellulose nanocrystals, Carbohydr. Polym. 157 (2017) 945–952, https://doi.org/10.1016/j.carbpol.2016.10.044.
[32] J.-W. Rhim, J.P. Reddy, X. Luo, Isolation of cellulose nanocrystals from onion skin and their utilization for the preparation of agar-based bio-nanocomposites films, Cellulose 22 (2015) 407–420, https://doi.org/10.1007/s10570-014-0517-7.
[33] Y. Gupte, A. Kulkarni, B. Raut, P. Sarkar, R. Choudhury, A. Chawande, G.R. K. Kumar, B. Bhadra, A. Satapathy, G. Das, B. Vishnupriya, S. Dasgupta, Characterization of nanocellulose production by strains of Komagataeibacter sp. isolated from organic waste and Kombucha, Carbohydr. Polym. 266 (2021) 118176, https://doi.org/10.1016/j.carbpol.2021.118176.
[34] S.S. Ahankari, A.R. Subhedar, S.S. Bhadauria, A. Dufresne, Nanocellulose in food packaging: a review, Carbohydr. Polym. 255 (2021) 117479, https://doi.org/10.1016/j.carbpol.2020.117479.
[35] B.M. Cherian, A.L. Leão, S.F. de Souza, S. Thomas, L.A. Pothan, M. Kottaisamy, Isolation of nanocellulose from pineapple leaf fibres by steam explosion, Carbohydr. Polym. 81 (2010) 720–725, https://doi.org/10.1016/j.carbpol.2010.03.046.
[36] K. Copenhaver, K. Li, M.E. Lamm, C. Walker, D. Johnson, Y. Han, L. Wang, X. Zhao, Y. Pu, H. Hinton, H. Tekinalp, S. Bhagia, A.J. Ragauskas, D.J. Gardner, S. Ozcan, Recycled cardboard containers as a low energy source for cellulose nanofibrils and their use in poly(<scp>l</scp> -lactide) nanocomposites, ACS Sustain. Chem. Eng. 9 (2021) 13460–13470, https://doi.org/10.1021/acssuschemeng.1c03890.
[37] P. Chawla, K. Sridhar, A. Kumar, P.K. Sarangi, A. Bains, M. Sharma, Production of nanocellulose from corn husk for the development of antimicrobial biodegradable packaging film, Int. J. Biol. Macromol. 242 (2023) 124805, https://doi.org/10.1016/j.ijbiomac.2023.124805.
[38] M. Vishnuvarthanan, R. Dharunya, S. Jayashree, B. Karpagam, R. Sowndharya, Environment-friendly packaging material: banana fiber/cowdung composite paperboard, Environ. Chem. Lett. 17 (2019) 1429–1434, https://doi.org/10.1007/s10311-019-00879-9.
[39] J. Eom, S. Park, H.-J. Jin, H.W. Kwak, Multiscale hybridization of natural silk–nanocellulose fibrous composites with exceptional mechanical properties, Front. Mater. 7 (2020), https://doi.org/10.3389/fmats.2020.00098.
[40] C. Amara, A. El Mahdi, R. Medimagh, K. Khwaldia, Nanocellulose-based composites for packaging applications, Curr. Opin. Green Sustain. Chem. 31 (2021) 100512, https://doi.org/10.1016/j.cogsc.2021.100512.
[41] J. Giri, R. Adhikari, A brief review on extraction of nanocellulose and its application, BIBECHANA 9 (2012) 81–87, https://doi.org/10.3126/bibechana.v9i0.7179.
[42] M.A. Hubbe, A. Ferrer, P. Tyagi, Y. Yin, C. Salas, L. Pal, O.J. Rojas, Nanocellulose in thin films, coatings, and plies for packaging applications: a review, Bioresources 12 (2017) 2143–2233, https://doi.org/10.15376/biores.12.1.2143-2233.
[43] S. Mateo, S. Peinado, F. Morillas-Gutiérrez, M.D. La Rubia, A.J. Moya, Nanocellulose from agricultural wastes: products and applications—a review, Processes 9 (2021) 1594, https://doi.org/10.3390/pr9091594.
[44] E.S. Iriani, A.W. Permana, S. Yuliani, S.I. Kailaku, A.A. Sulaiman, The effect of agricultural waste nanocellulose on the properties of bioplastic for fresh fruit packaging, IOP Conf. Ser. Earth Environ. Sci. 309 (2019) 012035, https://doi.org/10.1088/1755-1315/309/1/012035.
[45] C. Zhu, S. Monti, A.P. Mathew, Evaluation of nanocellulose interaction with water pollutants using nanocellulose colloidal probes and molecular dynamic simulations, Carbohydr. Polym. 229 (2020) 115510, https://doi.org/10.1016/j.carbpol.2019.115510.
[46] E. Espinosa, E. Rincón, R. Morcillo-Martín, L. Rabasco-Vílchez, A. Rodríguez, Orange peel waste biorefinery in multi-component cascade approach: polyphenolic compounds and nanocellulose for food packaging, Ind. Crop. Prod. 187 (2022) 115413, https://doi.org/10.1016/j.indcrop.2022.115413.
[47] A.B. Perumal, R.B. Nambiar, J.A. Moses, C. Anandharamakrishnan, Nanocellulose: recent trends and applications in the food industry, Food Hydrocoll. 127 (2022) 107484, https://doi.org/10.1016/j.foodhyd.2022.107484.
[48] L. Marchetti, S.C. Andrés, Use of nanocellulose in meat products, Curr. Opin. Food Sci. 38 (2021) 96–101, https://doi.org/10.1016/j.cofs.2020.11.003.
[49] R.K. Gupta, F.A. El Gawad, E.A.E. Ali, S. Karunanithi, P. Yugiani, P.P. Srivastav, Nanotechnology: current applications and future scope in food packaging systems, Meas. Food 13 (2024) 100131, https://doi.org/10.1016/j.meafoo.2023.100131.
[50] A.F. Alzate-Arbeláez, E. Dorta, C. López-Alarcón, F.B. Cortés, B.A. Rojano, Immobilization of Andean berry (Vaccinium meridionale) polyphenols on nanocellulose isolated from banana residues: a natural food additive with antioxidant properties, Food Chem. 294 (2019) 503–517, https://doi.org/10.1016/j.foodchem.2019.05.085.
[51] J. Chen, M. Huang, L. Kong, Flexible Ag/nanocellulose fibers SERS substrate and its applications for in-situ hazardous residues detection on food, Appl. Surf. Sci. 533 (2020) 147454, https://doi.org/10.1016/j.apsusc.2020.147454.
[52] S. Cui, M. Li, S. Zhang, J. Liu, Q. Sun, L. Xiong, Physicochemical properties of maize and sweet potato starches in the presence of cellulose nanocrystals, Food Hydrocoll. 77 (2018) 220–227, https://doi.org/10.1016/j.foodhyd.2017.09.037.
[53] G.M. DeLoid, I.S. Sohal, L.R. Lorente, R.M. Molina, G. Pyrgiotakis, A. Stevanovic, R. Zhang, D.J. McClements, N.K. Geitner, D.W. Bousfield, K.W. Ng, S.C.J. Loo, D. C. Bell, J. Brain, P. Demokritou, Reducing intestinal digestion and absorption of fat using a nature-derived biopolymer: interference of triglyceride hydrolysis by nanocellulose, ACS Nano 12 (2018) 6469–6479, https://doi.org/10.1021/acsnano.8b03074.
[54] F. Fahma, I. Febiyanti, N. Lisdayana, I.W. Arnata, D. Sartika, Nanocellulose as a new sustainable material for various applications: a review, Arch. Mater. Sci. Eng. 2 (2021) 49–64, https://doi.org/10.5604/01.3001.0015.2624.
[55] J.-H. Cherng, S.-C. Chou, C.-L. Chen, Y.-W. Wang, S.-J. Chang, G.-Y. Fan, F.-S. Leung, E. Meng, Bacterial cellulose as a potential bio-scaffold for effective re-epithelialization therapy, Pharmaceutics 13 (2021) 1592, https://doi.org/10.3390/pharmaceutics13101592.
[56] S.L. Arias, M.K. Cheng, A. Civantos, J. Devorkin, C. Jaramillo, J.P. Allain, Ion-induced nanopatterning of bacterial cellulose hydrogels for biosensing and anti-biofouling interfaces, ACS Appl. Nano Mater. 3 (2020) 6719–6728, https://doi.org/10.1021/acsanm.0c01151.
[57] S. Tortorella, V. Vetri Buratti, M. Maturi, L. Sambri, M. Comes Franchini, E. Locatelli, Surface-modified nanocellulose for application in biomedical engineering and nanomedicine: a review, Int. J. Nanomedicine 15 (2020) 9909–9937, https://doi.org/10.2147/IJN.S266103.
[58] M. Jorfi, E.J. Foster, Recent advances in nanocellulose for biomedical applications, J. Appl. Polym. Sci. 132 (2015), https://doi.org/10.1002/app.41719.
[59] N. Lin, A. Dufresne, Surface chemistry, morphological analysis and properties of cellulose nanocrystals with gradiented sulfation degrees, Nanoscale 6 (2014) 5384–5393, https://doi.org/10.1039/C3NR06761K.
[60] T. Aditya, J.P. Allain, C. Jaramillo, A.M. Restrepo, Surface modification of bacterial cellulose for biomedical applications, Int. J. Mol. Sci. 23 (2022) 610, https://doi.org/10.3390/ijms23020610.
[61] S. Afewerki, A. Sheikhi, S. Kannan, S. Ahadian, A. Khademhosseini, Gelatin-polysaccharide composite scaffolds for 3D cell culture and tissue engineering: towards natural therapeutics, Bioeng. Transl. Med. 4 (2019) 96–115, https://doi.org/10.1002/btm2.10124.
[62] D.O. de Castro, J. Bras, A. Gandini, N. Belgacem, Surface grafting of cellulose nanocrystals with natural antimicrobial rosin mixture using a green process, Carbohydr. Polym. 137 (2016) 1–8, https://doi.org/10.1016/j.carbpol.2015.09.101.

[63] B. Pula, S. Ramesh, S. Pamidipati, P. Doddipatla, A comparative study of greener alternatives for nanocellulose production from sugarcane bagasse, Bioresour. Bioprocess. 8 (2021) 132, https://doi.org/10.1186/s40643-021-00477-0.

[64] N.A. Abdullah, M.S.A. Rani, M. Mohammad, M.H. Sainorudin, N. Asim, Z. Yaakob, H. Razali, Z. Emdadi, Nanocellulose from agricultural waste as an emerging material for nanotechnology applications – an overview, Polimery 66 (2021) 157–168, https://doi.org/10.14314/polimery.2021.3.1.

[65] D. Verma, M. Okhawilai, S. Nangan, V.K. Thakur, S. Gopi, K. Kuppusamy, M. Sharma, H. Uyama, A sustainable and green approach towards the utilization of biopolymers for effective wound dressing applications: a detailed review, Nano-Struct. Nano-Objects 37 (2024) 101086, https://doi.org/10.1016/j.nanoso.2023.101086.

[66] A. Nzihou, K.P. Jibin, N. Kalarikkal, S. Thomas, Re-use and recycling of materials, river publishers, N. Y. (2022), https://doi.org/10.1201/9781003339304.

[67] M. González Martínez, M. Elsaddik, A. Nzihou, Monitoring, analysis, and quantification of hydrogen from biomass and biowaste: a review, Int. J. Hydrog. Energy 48 (2023) 22113–22131, https://doi.org/10.1016/j.ijhydene.2023.03.071.

[68] M.M. Ansari, Y. Heo, K. Do, M. Ghosh, Y.O. Son, Nanocellulose derived from agricultural biowaste by-products–sustainable synthesis, biocompatibility, biomedical applications, and future perspectives: a review, Carbohydr. Polym. Technol. and Appl. 8 (2024), https://doi.org/10.1016/j.carpta.2024.100529.

[69] L. Bacakova, J. Pajorova, M. Bacakova, A. Skogberg, P. Kallio, K. Kolarova, V. Svorcik, Versatile application of nanocellulose: from industry to skin tissue engineering and wound healing, Nanomaterials 9 (2019) 164, https://doi.org/10.3390/nano9020164.

[70] G.M. Oprică, D.M. Panaitescu, B.E. Lixandru, C.D. Uşurelu, A.R. Gabor, C.-A. Nicolae, R.C. Fierascu, A.N. Frone, Plant-derived nanocellulose with antibacterial activity for wound healing dressing, Pharmaceutics 15 (2023) 2672, https://doi.org/10.3390/pharmaceutics15122672.

[71] L. Song, Y. Li, Z. Xiong, L. Pan, Q. Luo, X. Xu, S. Lu, Water-induced shape memory effect of nanocellulose papers from sisal cellulose nanofibers with graphene oxide, Carbohydr. Polym. 179 (2018) 110–117, https://doi.org/10.1016/j.carbpol.2017.09.078.

[72] S.H. Song, K.Y. Seong, J.E. Kim, J. Go, E.K. Koh, J.E. Sung, H.J. Son, Y.J. Jung, H. S. Kim, J.T. Hong, D.Y. Hwang, Effects of different cellulose membranes regenerated from Styela clava tunics on wound healing, Int. J. Mol. Med. 39 (2017) 1173–1187, https://doi.org/10.3892/ijmm.2017.2923.

[73] A. Liu, H. Wu, A. Naeem, Q. Du, B. Ni, H. Liu, Z. Li, L. Ming, Cellulose nanocrystalline from biomass wastes: an overview of extraction, functionalization and applications in drug delivery, Int. J. Biol. Macromol. 241 (2023) 124557, https://doi.org/10.1016/j.ijbiomac.2023.124557.

[74] M. Ramesh, N. Vigneshwari, L. Rajeshkumar, Cellulose nanocrystals for drug delivery applications, in: Green Sustainable Process for Chemical and Environmental Engineering and Science, Elsevier, 2023, pp. 291–313, https://doi.org/10.1016/B978-0-323-95171-5.00012-1.

[75] S. Padhi, A. Singh, W. Routray, Nanocellulose from agro-waste: a comprehensive review of extraction methods and applications, Rev. Environ. Sci. Biotechnol. 22 (2023) 1–27, https://doi.org/10.1007/s11157-023-09643-6.

[76] Y. Yuan, S. Zhang, M. Ma, D. Wang, Y. Xu, Encapsulation and delivery of curcumin in cellulose nanocrystals nanoparticles using pH-driven method, LWT 155 (2022) 112863, https://doi.org/10.1016/j.lwt.2021.112863.

[77] S. Wang, Y. Lu, X. Ouyang, J. Ling, Fabrication of soy protein isolate/cellulose nanocrystal composite nanoparticles for curcumin delivery, Int. J. Biol. Macromol. 165 (2020) 1468–1474, https://doi.org/10.1016/j.ijbiomac.2020.10.046.

[78] M. Yusefi, M.L.-K. Soon, S.-Y. Teow, E.I. Monchouguy, B.N.H.M. Neerooa, Z. Izadiyan, H. Jahangirian, R. Rafiee-Moghaddam, T.J. Webster, K. Shameli, Fabrication of cellulose nanocrystals as potential anticancer drug delivery systems for colorectal cancer treatment, Int. J. Biol. Macromol. 199 (2022) 372–385, https://doi.org/10.1016/j.ijbiomac.2021.12.189.

[79] H.K. Pradeep, D.H. Patel, H.S. Onkarappa, C.C. Pratiksha, G.D. Prasanna, Role of nanocellulose in industrial and pharmaceutical sectors - a review, Int. J. Biol. Macromol. 207 (2022) 1038–1047, https://doi.org/10.1016/j.ijbiomac.2022.03.171.

[80] R. Kamel, N.A. Elkasabgy, An Overview on the Pharmaceutical Applications of Nanocellulose, 2023, pp. 395–411, https://doi.org/10.1007/978-981-99-2473-8_13.

[81] G. Chinga-Carrasco, Potential and limitations of nanocelluloses as components in biocomposite inks for three-dimensional bioprinting and for biomedical devices, Biomacromolecules 19 (2018) 701–711, https://doi.org/10.1021/acs.biomac.8b00053.

[82] C. Yadav, A. Saini, W. Zhang, X. You, I. Chauhan, P. Mohanty, X. Li, Plant-based nanocellulose: a review of routine and recent preparation methods with current progress in its applications as rheology modifier and 3D bioprinting, Int. J. Biol. Macromol. 166 (2021) 1586–1616, https://doi.org/10.1016/j.ijbiomac.2020.11.038.

[83] R.V. Badhe, A. Godse, A. Ahinkar, Biomaterials in 3D printing: a special emphasis on Nanocellulose, Indian J. Pharm. Educ. Res. 54 (2020) 526–540, https://doi.org/10.5530/ijper.54.3.101.

[84] V. Kuzmenko, E. Karabulut, E. Pernevik, P. Enoksson, P. Gatenholm, Tailor-made conductive inks from cellulose nanofibrils for 3D printing of neural guidelines, Carbohydr. Polym. 189 (2018) 22–30, https://doi.org/10.1016/j.carbpol.2018.01.097.

[85] O. Shoseyov, D. Kam, T. Ben Shalom, Z. Shtein, S. Vinkler, Y. Posen, Nanocellulose Composite Biomaterials in Industry and Medicine, 2019, pp. 693–784, https://doi.org/10.1007/978-3-030-12919-4_17.

[86] T. Möller, M. Amoroso, D. Hägg, C. Brantsing, N. Rotter, P. Apelgren, A. Lindahl, L. Kölby, P. Gatenholm, In vivo chondrogenesis in 3D bioprinted human cell-laden hydrogel constructs, Plast. Reconstr. Surg. Glob. Open 5 (2017) e1227, https://doi.org/10.1097/GOX.0000000000001227.

[87] B. Ren, X. Chen, S. Du, Y. Ma, H. Chen, G. Yuan, J. Li, D. Xiong, H. Tan, Z. Ling, Y. Chen, X. Hu, X. Niu, Injectable polysaccharide hydrogel embedded with hydroxyapatite and calcium carbonate for drug delivery and bone tissue engineering, Int. J. Biol. Macromol. 118 (2018) 1257–1266, https://doi.org/10.1016/j.ijbiomac.2018.06.200.

[88] L. Lin, S. Jiang, J. Yang, J. Qiu, X. Jiao, X. Yue, X. Ke, G. Yang, L. Zhang, Application of 3D-bioprinted nanocellulose and cellulose derivative-based bio-inks in bone and cartilage tissue engineering, Int. J. Bioprint. 9 (2022) 637, https://doi.org/10.18063/ijb.v9i1.637.

[89] A.C. Daly, G.M. Cunniffe, B.N. Sathy, O. Jeon, E. Alsberg, D.J. Kelly, 3D bioprinting of developmentally inspired templates for whole bone organ engineering, Adv. Healthc. Mater. 5 (2016) 2353–2362, https://doi.org/10.1002/adhm.201600182.

[90] A. De Mori, M. Peña Fernández, G. Blunn, G. Tozzi, M. Roldo, 3D printing and electrospinning of composite hydrogels for cartilage and bone tissue engineering, Polymers (Basel) 10 (2018) 285, https://doi.org/10.3390/polym10030285.

[91] J.G. Torres-Rendon, T. Femmer, L. De Laporte, T. Tigges, K. Rahimi, F. Gremse, S. Zafarnia, W. Lederle, S. Ifuku, M. Wessling, J.G. Hardy, A. Walther, Bioactive gyroid scaffolds formed by sacrificial templating of nanocellulose and nanochitin hydrogels as instructive platforms for biomimetic tissue engineering, Adv. Mater. 27 (2015) 2989–2995, https://doi.org/10.1002/adma.201405873.

[92] S. Gorgieva, L. Girandon, V. Kokol, Mineralization potential of cellulose-nanofibrils reinforced gelatine scaffolds for promoted calcium deposition by mesenchymal stem cells, Mater. Sci. Eng. C 73 (2017) 478–489, https://doi.org/10.1016/j.msec.2016.12.092.

[93] C. Ao, Y. Niu, X. Zhang, X. He, W. Zhang, C. Lu, Fabrication and characterization of electrospun cellulose/nano-hydroxyapatite nanofibers for bone tissue engineering, Int. J. Biol. Macromol. 97 (2017) 568–573, https://doi.org/10.1016/j.ijbiomac.2016.12.091.

[94] N. Ma, D.Y. Cheung, J.T. Butcher, Incorporating nanocrystalline cellulose into a multifunctional hydrogel for heart valve tissue engineering applications, J. Biomed. Mater. Res. A 110 (2022) 76–91, https://doi.org/10.1002/jbm.a.37267.

[95] S. Sakai, A. Yoshii, S. Sakurai, K. Horii, O. Nagasuna, Silk fibroin nanofibers: a promising ink additive for extrusion three-dimensional bioprinting, Mater. Today Bio. 8 (2020) 100078, https://doi.org/10.1016/j.mtbio.2020.100078.

[96] L. Bai, L.G. Greca, W. Xiang, J. Lehtonen, S. Huan, R.W.N. Nugroho, B.L. Tardy, O.J. Rojas, Adsorption and assembly of cellulosic and lignin colloids at oil/water interfaces, Langmuir 35 (2019) 571–588, https://doi.org/10.1021/acs.langmuir.8b01288.

[97] K. He, Q. Li, Y. Li, B. Li, S. Liu, Water-insoluble dietary fibers from bamboo shoot used as plant food particles for the stabilization of O/W Pickering emulsion, Food Chem. 310 (2020) 125925, https://doi.org/10.1016/j.foodchem.2019.125925.

[98] S.A. Kedzior, M.A. Dubé, E.D. Cranston, Cellulose nanocrystals and methyl cellulose as Costabilizers for nanocomposite latexes with double morphology, ACS Sustain. Chem. Eng. 5 (2017) 10509–10517, https://doi.org/10.1021/acssuschemeng.7b02510.

[99] A. Meftahi, P. Samyn, S.A. Geravand, R. Khajavi, S. Alibkhshi, M. Bechelany, A. Barhoum, Nanocelluloses as skin biocompatible materials for skincare, cosmetics, and healthcare: formulations, regulations, and emerging applications, Carbohydr. Polym. 278 (2022) 118956, https://doi.org/10.1016/j.carbpol.2021.118956.

[100] S.K. Dubey, A. Dey, G. Singhvi, M.M. Pandey, V. Singh, P. Kesharwani, Emerging trends of nanotechnology in advanced cosmetics, Colloids Surf. B: Biointerfaces 214 (2022) 112440, https://doi.org/10.1016/j.colsurfb.2022.112440.

[101] A.N. Nakagaito, S. Iwamoto, H. Yano, Bacterial cellulose: the ultimate nano-scalar cellulose morphology for the production of high-strength composites, Appl. Phys. A Mater. Sci. Process. 80 (2005) 93–97, https://doi.org/10.1007/s00339-004-2932-3.

[102] P. Srichola, K. Witthayolankowit, P. Sukyai, C. Sampoompuang, K. Lobyam, P. Kampakun, R. Toomtong, Recycling of nanocellulose from polyester–cotton textile waste for modification of film composites, Polymers (Basel) 15 (2023) 3324, https://doi.org/10.3390/polym15153324.

[103] G.Md.A. Khan, Md.S. Hasan, Md.H. Rahaman, A. Aydid, Md.M. Rahman, Md. Hasanuzzaman, R. Jahan, Md. Jannat-Al-Foisal, Cellulose and its Composites in Textiles and Food Industry, 2023, pp. 223–264, https://doi.org/10.1007/978-981-99-1655-9_9.

[104] D. Liang, W. Liu, T. Zhong, H. Liu, R. Dhandapani, H. Li, J. Wang, M. Wolcott, Nanocellulose reinforced lightweight composites produced from cotton waste via integrated nanofibrillation and compounding, Sci. Rep. 13 (2023) 2144, https://doi.org/10.1038/s41598-023-29335-z.

[105] M.-X. Ruiz-Caldas, J. Carlsson, I. Sadiktsis, A. Jaworski, U. Nilsson, A.P. Mathew, Cellulose nanocrystals from postconsumer cotton and blended fabrics: a study on their properties, chemical composition, and process efficiency, ACS Sustain. Chem. Eng. 10 (2022) 3787–3798, https://doi.org/10.1021/acssuschemeng.2c00797.

[106] M.G. Uddin, W. Batchelor, B.J. Allardyce, N. Byrne, C.J. Barrow, X. Wang, R. Rajkhowa, Preparing *Bombyx mori* silk nanofibers using a sustainable and

scalable approach, ACS Sustain. Chem. Eng. 8 (2020) 1155–1162, https://doi.org/10.1021/acssuschemeng.9b06138.
[107] Y. Chen, W. Yang, W. Wang, M. Zhang, M. Li, Bombyx mori silk fibroin scaffolds with Antheraea pernyi silk fibroin micro/nano fibers for promoting EA. hy926 cell proliferation, Materials 10 (2017) 1153, https://doi.org/10.3390/ma10101153.
[108] L. Abate, A. Bachheti, R.K. Bachheti, A. Husen, D.P. Pandey, M.B. Megra, Coir fiber-based cellulose, nanocellulose, and their cutting-edge applications, in: Coir Fiber and its Composites, Elsevier, 2022, pp. 309–331, https://doi.org/10.1016/B978-0-443-15186-6.00060-6.
[109] M.N. Rojas-Valencia, E. Galeana-Olvera, D.Y. Fernández-Rojas, C. Mendoza-Buenrostro, H.A. Nájera-Aguilar, M. Vaca-Mier, Isolation of cellulose nanofibrils from coconut waste for the production of sewing thread, Adv. Mater. Sci. 3 (2018), https://doi.org/10.15761/AMS.1000135.
[110] R. Reshmy, E. Philip, S.A. Paul, A. Madhavan, R. Sindhu, P. Binod, A. Pandey, R. Sirohi, Nanocellulose-based products for sustainable applications-recent trends and possibilities, Rev. Environ. Sci. Biotechnol. 19 (2020) 779–806, https://doi.org/10.1007/s11157-020-09551-z.
[111] L. Spagnuolo, R. D'Orsi, A. Operamolla, Nanocellulose for paper and textile coating: the importance of surface chemistry, Chempluschem 87 (2022), https://doi.org/10.1002/cplu.202200204.
[112] L.P.C. Silva, N.A. de Oliveira, R.S. Valotto, F.C. Monteiro, L.A.C. Alvarez, L. M. Cesário, T.É.C. Zanardo, A.P.M.C. Nilo, R.P. Schuenck, J.P. de Oliveira, F. V. Campos, M.C.C. Guimarães, Cellulose nanofibers infused with pomegranate gold nanoparticles display antibacterial activity, Nano-Struct. Nano-Objects 36 (2023) 101045, https://doi.org/10.1016/j.nanoso.2023.101045.
[113] G. Nocca, A. Arcovito, N.A. Elkasabgy, M. Basha, N. Giacon, E. Mazzinelli, M. S. Abdel-Maksoud, R. Kamel, Cellulosic textiles—an appealing trend for different pharmaceutical applications, Pharmaceutics 15 (2023) 2738, https://doi.org/10.3390/pharmaceutics15122738.
[114] T. Feczkó, M. Kovács, B. Voncina, Improvement of fatigue resistance of spirooxazine in ethyl cellulose and poly(methyl methacrylate) nanoparticles using a hindered amine light stabilizer, J. Photochem. Photobiol. A Chem. 247 (2012) 1–7, https://doi.org/10.1016/j.jphotochem.2012.08.001.
[115] R.R. Mather, R.H. Wardman, S. Rana, The chemistry of textile fibres, R. Soc. Chem. (2023), https://doi.org/10.1039/9781837670505.
[116] D.A. Gopakumar, A.R. Pai, Y.B. Pottathara, D. Pasquini, L. Carlos de Morais, M. Luke, N. Kalarikkal, Y. Grohens, S. Thomas, Cellulose nanofiber-based polyaniline flexible papers as sustainable microwave absorbers in the X-band, ACS Appl. Mater. Interfaces 10 (2018) 20032–20043, https://doi.org/10.1021/acsami.8b04549.
[117] R. Prasad, A.R. Pai, S.O. Oyadiji, S. Thomas, S.K.S. Parashar, Utilization of hazardous red mud in silicone rubber/MWCNT nanocomposites for high performance electromagnetic interference shielding, J. Clean. Prod. 377 (2022) 134290, https://doi.org/10.1016/j.jclepro.2022.134290.
[118] A.R. Pai, S.M. Thomas, S. Thomas, Polysaccharide-based nanocomposites for energy-harvesting nanogenerators, in: Engineered Polymer Nanocomposites for Energy Harvesting Applications, Elsevier, 2022: pp. 159–180. doi:https://doi.org/10.1016/B978-0-12-824155-4.00006-5.
[119] A.A.B. Omran, A.A.B.A. Mohammed, S.M. Sapuan, R.A. Ilyas, M.R.M. Asyraf, S. S. Rahimian Koloor, M. Petrů, Micro- and nanocellulose in polymer composite materials: a review, Polymers (Basel) 13 (2021) 231, https://doi.org/10.3390/polym13020231.
[120] Y. Habibi, L.A. Lucia, O.J. Rojas, Cellulose nanocrystals: chemistry, self-assembly, and applications, Chem. Rev. 110 (2010) 3479–3500, https://doi.org/10.1021/cr900339w.
[121] T. Ayisha Naziba, D. Praveen Kumar, S. Karthikeyan, S. Sriramajayam, M. Djanaguiraman, S. Sundaram, M. Ghamari, R. Prasada Rao, S. Ramakrishna, D. Ramesh, Biomass derived biofluorescent carbon dots for energy applications: current progress and prospects, Chem. Rec. (2024), https://doi.org/10.1002/tcr.202400030.
[122] R. Pramanik, A. Arockiarajan, Mechanical and morphological characterization of a novel silk/cellulose-based soft composite, Mater. Lett. 314 (2022) 131871, https://doi.org/10.1016/j.matlet.2022.131871.
[123] Q. Chen, J. Xiong, G. Chen, T. Tan, Preparation and characterization of highly transparent hydrophobic nanocellulose film using corn husks as main material, Int. J. Biol. Macromol. 158 (2020) 781–789, https://doi.org/10.1016/j.ijbiomac.2020.04.250.
[124] A.A. Septevani, A. Rifathin, A.A. Sari, Y. Sampora, G.N. Ariani, Sudiyarmanto, D. Sondari, Oil palm empty fruit bunch-based nanocellulose as a super-adsorbent for water remediation, Carbohydr. Polym. 229 (2020) 115433, https://doi.org/10.1016/j.carbpol.2019.115433.
[125] A. Atiqah, F.A. Sabaruddin, N. Ismail, A. Jalar, M.A. Bakar, A.A. Hamzah, R. A. Ilyas, M. Asrofi, Nanocellulose composites for electronic applications, in: Industrial Applications of Nanocellulose and its Nanocomposites, Elsevier, 2022, pp. 481–502, https://doi.org/10.1016/B978-0-323-89909-3.00001-8.
[126] A.A. Septevani, D. Burhani, Y. Sampora, Nanocellulose in electronics and electrical industry, in: Nanocellulose Materials, Elsevier, 2022, pp. 217–246, https://doi.org/10.1016/B978-0-12-823963-6.00010-7.
[127] Q. Luo, H. Shen, G. Zhou, X. Xu, A mini-review on the dielectric properties of cellulose and nanocellulose-based materials as electronic components, Carbohydr. Polym. 303 (2023) 120449, https://doi.org/10.1016/j.carbpol.2022.120449.
[128] A. Subhedar, S. Bhadauria, S. Ahankari, H. Kargarzadeh, Nanocellulose in biomedical and biosensing applications: a review, Int. J. Biol. Macromol. 166 (2021) 587–600, https://doi.org/10.1016/j.ijbiomac.2020.10.217.
[129] J. Jose, A.R. Pai, D.A. Gopakumar, Y. Dalvi, V. Ruby, S.G. Bhat, D. Pasquini, N. Kalarikkal, S. Thomas, Novel 3D porous aerogels engineered at nano scale from cellulose nano fibers and curcumin: an effective treatment for chronic wounds, Carbohydr. Polym. 287 (2022) 119338, https://doi.org/10.1016/j.carbpol.2022.119338.
[130] M.L. Soriano, M.J. Dueñas-Mas, Promising Sensing Platforms Based on Nanocellulose, 2018, pp. 273–301, https://doi.org/10.1007/5346_2018_26.
[131] A. Horta-Velázquez, E. Morales-Narváez, Nanocellulose in wearable sensors, Green Anal. Chem. 1 (2022) 100009, https://doi.org/10.1016/j.greeac.2022.100009.
[132] W. Gao, S. Emaminejad, H.Y.Y. Nyein, S. Challa, K. Chen, A. Peck, H.M. Fahad, H. Ota, H. Shiraki, D. Kiriya, D.-H. Lien, G.A. Brooks, R.W. Davis, A. Javey, Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis, Nature 529 (2016) 509–514, https://doi.org/10.1038/nature16521.
[133] R. Das, S. Nag, P. Banerjee, Electrochemical nanosensors for sensitization of sweat metabolites: from concept mapping to personalized health monitoring, Molecules 28 (2023) 1259, https://doi.org/10.3390/molecules28031259.
[134] S. Banerjee, G. Slaughter, A tattoo-like glucose abiotic biofuel cell, J. Electroanal. Chem. 904 (2022) 115941, https://doi.org/10.1016/j.jelechem.2021.115941.
[135] M.M. Abdi, R.L. Razalli, P.M. Tahir, N. Chaibakhsh, M. Hassani, M. Mir, Optimized fabrication of newly cholesterol biosensor based on nanocellulose, Int. J. Biol. Macromol. 126 (2019) 1213–1222, https://doi.org/10.1016/j.ijbiomac.2019.01.001.
[136] S.S. Danewalia, G. Sharma, S. Thakur, K. Singh, Agricultural wastes as a resource of raw materials for developing low-dielectric glass-ceramics, Sci. Rep. 6 (2016) 24617, https://doi.org/10.1038/srep24617.
[137] R. Mahani, A.Kh. Helmy, A.M. Fathi, Electrical, optical, and electrochemical performances of phosphate-glasses-doped with ZnO and CuO and their composite with polyaniline, Sci. Rep. 14 (2024) 1169, https://doi.org/10.1038/s41598-023-51065-5.
[138] G. Sharma, M. Kaur, S. Punj, K. Singh, Biomass as a sustainable resource for value-added modern materials: a review, Biofuels Bioprod. Biorefin. 14 (2020) 673–695, https://doi.org/10.1002/bbb.2079.
[139] S. Zhang, T. Chen, Y. Xiong, Q. Dong, Effects of wet torrefaction on the physicochemical properties and pyrolysis product properties of rice husk, Energy Convers. Manag. 141 (2017) 403–409, https://doi.org/10.1016/j.enconman.2016.10.002.
[140] V.M. Pereira, M.V.T. Heckler, M.A.Z. Vasconcellos, E.W. de Menezes, L.E. G. Armas, Characterization of dielectric properties of residual ashes obtained from rice husk and annoni grass, Sci. Rep. 13 (2023) 14478, https://doi.org/10.1038/s41598-023-40887-y.
[141] S.K. Tiwari, M. Bystrzejewski, A. De Adhikari, A. Huczko, N. Wang, Methods for the conversion of biomass waste into value-added carbon nanomaterials: recent progress and applications, Prog. Energy Combust. Sci. 92 (2022) 101023, https://doi.org/10.1016/j.pecs.2022.101023.
[142] F. Baraka, J. Labidi, The emergence of nanocellulose aerogels in CO2 adsorption, Sci. Total Environ. 912 (2024) 169093, https://doi.org/10.1016/j.scitotenv.2023.169093.
[143] W. Zhu, M. Chen, J. Jang, M. Han, Y. Moon, J. Kim, J. You, S. Li, T. Park, J. Kim, Amino-functionalized nanocellulose aerogels for the superior adsorption of CO2 and separation of CO2/CH4 mixture gas, Carbohydr. Polym. 323 (2024) 121393, https://doi.org/10.1016/j.carbpol.2023.121393.
[144] N.A.D. Ho, C.P. Leo, A review on the emerging applications of cellulose, cellulose derivatives and nanocellulose in carbon capture, Environ. Res. 197 (2021) 111100, https://doi.org/10.1016/j.envres.2021.111100.
[145] S.K. Gebremariam, L.F. Dumée, P.L. Llewellyn, Y.F. AlWahedi, G.N. Karanikolos, Metal-organic framework hybrid adsorbents for carbon capture – a review, J. Environ. Chem. Eng. 11 (2023) 109291, https://doi.org/10.1016/j.jece.2023.109291.
[146] V.J. Oghenekohwo, A.A. Maamoun, S. Zulfiqar, M.J. Forrester, V. Slovák, T.-P. Wang, E.W. Cochran, Unlocking the potential of polymeric aerogels from food and agricultural waste for sustainable CO_2 capture, ACS Appl. Polym. Mater. 6 (2024) 638–648, https://doi.org/10.1021/acsapm.3c02269.
[147] J. Wei, S. Geng, J. Hedlund, K. Oksman, Lightweight, flexible, and multifunctional anisotropic nanocellulose-based aerogels for CO2 adsorption, Cellulose 27 (2020) 2695–2707, https://doi.org/10.1007/s10570-019-02935-7.
[148] D.A. Gopakumar, V. Arumughan, D. Pasquini, S.-Y. Leu, A.K. H.P.S., S. Thomas, Nanocellulose-based membranes for water purification, in: Nanoscale Materials in Water Purification, Elsevier, 2019, pp. 59–85, https://doi.org/10.1016/B978-0-12-813926-4.00004-5.
[149] S. Wang, Q. Zhang, Z. Wang, J. Pu, Facile fabrication of an effective nanocellulose-based aerogel and removal of methylene blue from aqueous system, J. Water Process Eng. 37 (2020) 101511, https://doi.org/10.1016/j.jwpe.2020.101511.
[150] D.A. Gopakumar, D. Pasquini, M.A. Henrique, L.C. de Morais, Y. Grohens, S. Thomas, Meldrum's acid modified cellulose nanofiber-based polyvinylidene fluoride microfiltration membrane for dye water treatment and nanoparticle removal, ACS Sustain. Chem. Eng. 5 (2017) 2026–2033, https://doi.org/10.1021/acssuschemeng.6b02952.
[151] N. Amiralian, M. Mustapic, Md.S.A. Hossain, C. Wang, M. Konarova, J. Tang, J. Na, A. Khan, A. Rowan, Magnetic nanocellulose: a potential material for removal of dye from water, J. Hazard. Mater. 394 (2020) 122571, https://doi.org/10.1016/j.jhazmat.2020.122571.
[152] A. Tshikovhi, S.B. Mishra, A.K. Mishra, Nanocellulose-based composites for the removal of contaminants from wastewater, Int. J. Biol. Macromol. 152 (2020) 616–632, https://doi.org/10.1016/j.ijbiomac.2020.02.221.

[153] A.W. Carpenter, C.-F. de Lannoy, M.R. Wiesner, Cellulose nanomaterials in water treatment technologies, Environ. Sci. Technol. 49 (2015) 5277–5287, https://doi.org/10.1021/es506351r.
[154] J. Tang, Y. Song, F. Zhao, S. Spinney, J. da Silva Bernardes, K.C. Tam, Compressible cellulose nanofibril (CNF) based aerogels produced via a bio-inspired strategy for heavy metal ion and dye removal, Carbohydr. Polym. 208 (2019) 404–412, https://doi.org/10.1016/j.carbpol.2018.12.079.
[155] R.J. Moon, A. Martini, J. Nairn, J. Simonsen, J. Youngblood, Cellulose nanomaterials review: structure, properties and nanocomposites, Chem. Soc. Rev. 40 (2011) 3941, https://doi.org/10.1039/c0cs00108b.
[156] N.S. Sharip, T.A.T. Yasim-Anuar, M.N.F. Norrrahim, S.S. Shazleen, N. Mohd, S. M. Nurazzi, R.A. Ilyas Sapuan, A review on nanocellulose composites in biomedical application, in: Composites in Biomedical Applications, CRC Press, 2020, pp. 161–190, https://doi.org/10.1201/9780429327766-8.
[157] N.G. Olaiya, A.A. Oyekanmi, M.M. Hanafiah, T.O. Olugbade, M.K. Adeyeri, F. G. Olaiya, Enzyme-assisted extraction of nanocellulose from textile waste: a review on production technique and applications, Bioresour. Technol. Rep. 19 (2022) 101183, https://doi.org/10.1016/j.biteb.2022.101183.
[158] N.P. Klochko, V.A. Barbash, K.S. Klepikova, V.R. Kopach, I.I. Tyukhov, O. V. Yashchenko, D.O. Zhadan, S.I. Petrushenko, S.V. Dukarov, V.M. Lyubov, A. L. Khrypunova, Use of biomass for a development of nanocellulose-based biodegradable flexible thin film thermoelectric material, Sol. Energy 201 (2020) 21–27, https://doi.org/10.1016/j.solener.2020.02.091.
[159] J. Wang, X. Han, C. Zhang, K. Liu, G. Duan, Source of nanocellulose and its application in nanocomposite packaging material: a review, Nanomaterials 12 (2022) 3158, https://doi.org/10.3390/nano12183158.
[160] M. Rajinipriya, M. Nagalakshmaiah, M. Robert, S. Elkoun, Importance of agricultural and industrial waste in the field of nanocellulose and recent industrial developments of wood based nanocellulose: a review, ACS Sustain. Chem. Eng. 6 (2018) 2807–2828, https://doi.org/10.1021/acssuschemeng.7b03437.
[161] Y. Ko, G. Kwon, H. Choi, K. Lee, Y. Jeon, S. Lee, J. Kim, J. You, Cutting edge use of conductive patterns in nanocellulose-based green electronics, Adv. Funct. Mater. 33 (2023), https://doi.org/10.1002/adfm.202302785.
[162] C. Sharma, N.K. Bhardwaj, Bacterial nanocellulose: present status, biomedical applications and future perspectives, Mater. Sci. Eng. C 104 (2019) 109963, https://doi.org/10.1016/j.msec.2019.109963.
[163] H. Zhu, W. Luo, P.N. Ciesielski, Z. Fang, J.Y. Zhu, G. Henriksson, M.E. Himmel, L. Hu, Wood-derived materials for green electronics, biological devices, and energy applications, Chem. Rev. 116 (2016) 9305–9374, https://doi.org/10.1021/acs.chemrev.6b00225.
[164] M.A. Hubbe, A. Ferrer, P. Tyagi, Y. Yin, C. Salas, L. Pal, O.J. Rojas, Nanocellulose in thin films, coatings, and plies for packaging applications: a review, Bioresources 12 (2017) 2143–2233, https://doi.org/10.15376/biores.12.1.2143-2233.
[165] Z. Kamble, B.K. Behera, Sustainable hybrid composites reinforced with textile waste for construction and building applications, Constr. Build. Mater. 284 (2021) 122800, https://doi.org/10.1016/j.conbuildmat.2021.122800.
[166] S.S. Konganapuram Narasimma Bharathi, V. Adiga, S. Khasnabis, B. Nath, N. A. Khan, P.C. Ramamurthy, Study of nano cellulose-based membrane tailorable biodegradability for use in the packaging application of electronic devices, Chemosphere 309 (2022) 136683, https://doi.org/10.1016/j.chemosphere.2022.136683.
[167] V. Thakur, A. Guleria, S. Kumar, S. Sharma, K. Singh, Recent advances in nanocellulose processing, functionalization and applications: a review, Mater. Adv. 2 (2021) 1872–1895, https://doi.org/10.1039/D1MA00049G.
[168] H.K. Pradeep, D.H. Patel, H.S. Onkarappa, C.C. Pratiksha, G.D. Prasanna, Role of nanocellulose in industrial and pharmaceutical sectors - a review, Int. J. Biol. Macromol. 207 (2022) 1038–1047, https://doi.org/10.1016/j.ijbiomac.2022.03.171.
[169] X. Du, Z. Zhang, W. Liu, Y. Deng, Nanocellulose-based conductive materials and their emerging applications in energy devices - a review, Nano Energy 35 (2017) 299–320, https://doi.org/10.1016/j.nanoen.2017.04.001.
[170] A.A.B. Omran, A.A.B.A. Mohammed, S.M. Sapuan, R.A. Ilyas, M.R.M. Asyraf, S. S. Rahimian Koloor, M. Petrů, Micro- and nanocellulose in polymer composite materials: a review, Polymers (Basel) 13 (2021) 231, https://doi.org/10.3390/polym13020231.
[171] W. Soboyejo, Mechanical Properties of Engineered Materials, CRC Press, 2002, https://doi.org/10.1201/9780203910399.
[172] D. Trache, A.F. Tarchoun, M. Derradji, T.S. Hamidon, N. Masruchin, N. Brosse, M. H. Hussin, Nanocellulose: from fundamentals to advanced applications, Front. Chem. 8 (2020), https://doi.org/10.3389/fchem.2020.00392.
[173] N. Yildirim, S. Shaler, A study on thermal and nanomechanical performance of cellulose nanomaterials (CNs), Materials 10 (2017) 718, https://doi.org/10.3390/ma10070718.
[174] X. Wang, C.H. Chang, J. Jiang, Q. Liu, Y. Liao, J. Lu, L. Li, X. Liu, J. Kim, A. Ahmed, A.E. Nel, T. Xia, The crystallinity and aspect ratio of cellulose nanomaterials determine their pro-inflammatory and immune adjuvant effects in vitro and in vivo, Small 15 (2019), https://doi.org/10.1002/smll.201901642.
[175] M. Fodil Cherif, D. Trache, N. Brosse, F. Benaliouche, A.F. Tarchoun, Comparison of the physicochemical properties and thermal stability of organosolv and Kraft Lignins from hardwood and softwood biomass for their potential valorization, Waste Biomass Valoriz. 11 (2020) 6541–6553, https://doi.org/10.1007/s12649-020-00955-0.
[176] A. Dufresne, M.N. Belgacem, Cellulose-reinforced composites: from micro-to nanoscale, Polym. Sci. Tecnol. 20 (2010) 1–10, https://doi.org/10.4322/polimeros.2010.01.001.
[177] H. Kargarzadeh, I. Ahmad, S. Thomas, A. Dufresne (Eds.), Handbook of Nanocellulose and Cellulose Nanocomposites, Wiley, 2017, https://doi.org/10.1002/9783527689972.
[178] K. De France, Z. Zeng, T. Wu, G. Nyström, Nanocellulose: functional materials from nanocellulose: utilizing structure–property relationships in bottom-up fabrication (Adv. Mater. 28/2021), Adv. Mater. 33 (2021), https://doi.org/10.1002/adma.202170216.
[179] S. Ahankari, P. Paliwal, A. Subhedar, H. Kargarzadeh, Recent developments in nanocellulose-based aerogels in thermal applications: a review, ACS Nano 15 (2021) 3849–3874, https://doi.org/10.1021/acsnano.0c09678.
[180] M. Börjesson, G. Westman, Crystalline nanocellulose — preparation, modification, and properties, in: cellulose - fundamental aspects and current trends, InTech (2015), https://doi.org/10.5772/61899.
[181] A. Santmartí, K.-Y. Lee, Crystallinity and thermal stability of nanocellulose, in: Nanocellulose and Sustainability, CRC Press, Series: Sustainability contributions through science and technology, 2018, CRC Press, Boca Raton, 2018, pp. 67–86, https://doi.org/10.1201/9781351262927-5.
[182] Z. Chen, Y. Hu, G. Shi, H. Zhuo, M.A. Ali, E. Jamróz, H. Zhang, L. Zhong, X. Peng, Advanced flexible materials from nanocellulose, Adv. Funct. Mater. 33 (2023), https://doi.org/10.1002/adfm.202214245.
[183] V. Apostolopoulou-Kalkavoura, P. Munier, L. Bergström, Thermally insulating Nanocellulose-based materials, Adv. Mater. 33 (2021), https://doi.org/10.1002/adma.202001839.
[184] A. Dufresne, Nanocellulose: a new ageless bionanomaterial, Mater. Today 16 (2013) 220–227, https://doi.org/10.1016/j.mattod.2013.06.004.
[185] L. Bao, J. Tang, F.F. Hong, X. Lu, L. Chen, Physicochemical properties and in vitro biocompatibility of three bacterial nanocellulose conduits for blood vessel applications, Carbohydr. Polym. 239 (2020) 116246, https://doi.org/10.1016/j.carbpol.2020.116246.
[186] P. Niu, H. Mao, K.H. Lim, Q. Wang, W.-J. Wang, X. Yang, Nanocellulose-based hollow fibers for advanced water and moisture management, ACS Nano 17 (2023) 14686–14694, https://doi.org/10.1021/acsnano.3c02553.
[187] C. Vilela, A.J.D. Silvestre, F.M.L. Figueiredo, C.S.R. Freire, Nanocellulose-based materials as components of polymer electrolyte fuel cells, J. Mater. Chem. A Mater. 7 (2019) 20045–20074, https://doi.org/10.1039/C9TA07466J.
[188] Y. Kobayashi, T. Saito, A. Isogai, Aerogels with 3D ordered nanofiber skeletons of liquid-crystalline nanocellulose derivatives as tough and transparent insulators, Angew. Chem. Int. Ed. 53 (2014) 10394–10397, https://doi.org/10.1002/anie.201405123.
[189] V.C. Midhun, S. Suresh, B. Praveen, C.R. Raj, Effect of vacuum insulation panel on active thermal management for electronics system exposed to thermal radiation, Therm. Sci. Eng. Progr. 26 (2021) 101117, https://doi.org/10.1016/j.tsep.2021.101117.
[190] D.Y. Liu, G.X. Sui, D. Bhattacharyya, Synthesis and characterisation of nanocellulose-based polyaniline conducting films, Compos. Sci. Technol. 99 (2014) 31–36, https://doi.org/10.1016/j.compscitech.2014.05.001.
[191] K. Uetani, K. Hatori, Thermal conductivity analysis and applications of nanocellulose materials, Sci. Technol. Adv. Mater. 18 (2017) 877–892, https://doi.org/10.1080/14686996.2017.1390692.
[192] A. Tayeb, E. Amini, S. Ghasemi, M. Tajvidi, Cellulose nanomaterials—binding properties and applications: a review, Molecules 23 (2018) 2684, https://doi.org/10.3390/molecules23102684.
[193] H.V. Scheller, P. Ulvskov, Hemicelluloses, Annu. Rev. Plant Biol. 61 (2010) 263–289, https://doi.org/10.1146/annurev-arplant-042809-112315.
[194] F.J. Ruiz-Dueñas, Á.T. Martínez, Microbial degradation of lignin: how a bulky recalcitrant polymer is efficiently recycled in nature and how we can take advantage of this, Microb. Biotechnol. 2 (2009) 164–177, https://doi.org/10.1111/j.1751-7915.2008.00078.x.
[195] P. Phanthong, P. Reubroycharoen, X. Hao, G. Xu, A. Abudula, G. Guan, Nanocellulose: extraction and application, Carbon Resour. Convers. 1 (2018) 32–43, https://doi.org/10.1016/j.crcon.2018.05.004.
[196] M.M.Á.D. Maciel, K.C.C. de C. Benini, H.J.C. Voorwald, M.O.H. Cioffi, Obtainment and characterization of nanocellulose from an unwoven industrial textile cotton waste: effect of acid hydrolysis conditions, Int. J. Biol. Macromol. 126 (2019) 496–506, https://doi.org/10.1016/j.ijbiomac.2018.12.202.
[197] A.G. de Souza, R.F.S. Barbosa, D.S. Rosa, Nanocellulose from industrial and agricultural waste for further use in PLA composites, J. Polym. Environ. 28 (2020) 1851–1868, https://doi.org/10.1007/s10924-020-01731-w.
[198] S. Puri, S. Sharma, A. Kumari, M. Sharma, U. Sharma, S. Kumar, Extraction of lignocellulosic constituents from cow dung: preparation and characterisation of nanocellulose, Biomass Convers. Biorefinery 13 (2023) 311–320, https://doi.org/10.1007/s13399-020-01119-9.
[199] M. Nogi, S. Iwamoto, A.N. Nakagaito, H. Yano, Optically transparent nanofiber paper, Adv. Mater. 21 (2009) 1595–1598, https://doi.org/10.1002/adma.200803174.
[200] M.E. Gibril, P. Lekha, J. Andrew, B. Sithole, T. Tesfaye, D. Ramjugernath, Beneficiation of pulp and paper mill sludge: production and characterisation of functionalised crystalline nanocellulose, Clean Techn. Environ. Policy 20 (2018) 1835–1845, https://doi.org/10.1007/s10098-018-1578-3.
[201] A. Espert, F. Vilaplana, S. Karlsson, Comparison of water absorption in natural cellulosic fibres from wood and one-year crops in polypropylene composites and its influence on their mechanical properties, Compos. Part A Appl. Sci. Manuf. 35 (2004) 1267–1276, https://doi.org/10.1016/j.compositesa.2004.04.004.

[202] K. Daicho, K. Kobayashi, S. Fujisawa, T. Saito, Crystallinity-independent yet modification-dependent true density of nanocellulose, Biomacromolecules 21 (2020) 939–945, https://doi.org/10.1021/acs.biomac.9b01584.
[203] A. Kafy, H.C. Kim, L. Zhai, J.W. Kim, L. Van Hai, T.J. Kang, J. Kim, Cellulose long fibers fabricated from cellulose nanofibers and its strong and tough characteristics, Sci. Rep. 7 (2017) 17683, https://doi.org/10.1038/s41598-017-17713-3.
[204] V. Raju, R. Revathiswaran, K.S. Subramanian, K.T. Parthiban, K. Chandrakumar, E.V. Anoop, C.J. Chirayil, Isolation and characterization of nanocellulose from selected hardwoods, viz., Eucalyptus tereticornis Sm. and Casuarina equisetifolia L., by steam explosion method, Sci. Rep. 13 (2023) 1199, https://doi.org/10.1038/s41598-022-26600-5.
[205] W. Chen, H. Yu, Y. Liu, P. Chen, M. Zhang, Y. Hai, Individualization of cellulose nanofibers from wood using high-intensity ultrasonication combined with chemical pretreatments, Carbohydr. Polym. 83 (2011) 1804–1811, https://doi.org/10.1016/j.carbpol.2010.10.040.
[206] O.D. Fagbemi, J.E. Andrew, B. Sithole, Beneficiation of wood sawdust into cellulose nanocrystals for application as a bio-binder in the manufacture of particleboard, Biomass Convers. Biorefinery 13 (2023) 11645–11656, https://doi.org/10.1007/s13399-021-02015-6.
[207] A. Isogai, Wood nanocelluloses: fundamentals and applications as new bio-based nanomaterials, J. Wood Sci. 59 (2013) 449–459, https://doi.org/10.1007/s10086-013-1365-z.
[208] J. Bang, H. Lee, Y. Yang, J.-K. Oh, H.W. Kwak, Nano/Micro hybrid bamboo fibrous preforms for robust biodegradable fiber reinforced plastics, Polymers (Basel) 13 (2021) 636, https://doi.org/10.3390/polym13040636.
[209] R.M. dos Santos, W.P. Flauzino Neto, H.A. Silvério, D.F. Martins, N.O. Dantas, D. Pasquini, Cellulose nanocrystals from pineapple leaf, a new approach for the reuse of this agro-waste, Ind. Crop. Prod. 50 (2013) 707–714, https://doi.org/10.1016/j.indcrop.2013.08.049.
[210] M. Yu, R. Yang, L. Huang, X. Cao, F. Yang, D. Liu, Preparation and characterization of bamboo nanocrystalline cellulose, Bioresources 7 (2012), https://doi.org/10.15376/biores.7.2.1802-1812.
[211] D. Liang, W. Liu, T. Zhong, H. Liu, R. Dhandapani, H. Li, J. Wang, M. Wolcott, Nanocellulose reinforced lightweight composites produced from cotton waste via integrated nanofibrillation and compounding, Sci. Rep. 13 (2023) 2144, https://doi.org/10.1038/s41598-023-29335-z.
[212] M. Li, B. He, Y. Chen, L. Zhao, Physicochemical properties of nanocellulose isolated from cotton stalk waste, ACS Omega 6 (2021) 25162–25169, https://doi.org/10.1021/acsomega.1c02568.
[213] X. Yang, L. Li, W. Zhao, M. Wang, W. Yang, Y. Tian, R. Zheng, S. Deng, Y. Mu, X. Zhu, Characteristics and functional application of cellulose fibers extracted from cow dung wastes, Materials 16 (2023) 648, https://doi.org/10.3390/ma16020648.
[214] V.A. Barbash, O.V. Yaschenko, O.M. Shniruk, Preparation and properties of nanocellulose from organosolv straw pulp, Nanoscale Res. Lett. 12 (2017) 241, https://doi.org/10.1186/s11671-017-2001-4.
[215] M. Gorbunova, L. Grunin, R.H. Morris, A. Imamutdinova, Nanocellulose-based thermoplastic polyurethane biocomposites with shape memory effect, J. Compos. Sci. 7 (2023) 168, https://doi.org/10.3390/jcs7040168.
[216] O.M. Vanderfleet, M.S. Reid, J. Bras, L. Heux, J. Godoy-Vargas, M.K.R. Panga, E. D. Cranston, Insight into thermal stability of cellulose nanocrystals from new hydrolysis methods with acid blends, Cellulose 26 (2019) 507–528, https://doi.org/10.1007/s10570-018-2175-7.
[217] V.A. Barbash, O.V. Yashchenko, Preparation and application of nanocellulose from non-wood plants to improve the quality of paper and cardboard, Appl. Nanosci. 10 (2020) 2705–2716, https://doi.org/10.1007/s13204-019-01242-8.
[218] M. Mariano, N. El Kissi, A. Dufresne, Cellulose nanocrystals and related nanocomposites: review of some properties and challenges, J. Polym. Sci. B Polym. Phys. 52 (2014) 791–806, https://doi.org/10.1002/polb.23490.
[219] D. Huang, H. Hong, W. Huang, H. Zhang, X. Hong, Scalable preparation of cellulose nanofibers from office waste paper by an environment-friendly method, Polymers (Basel) 13 (2021) 3119, https://doi.org/10.3390/polym13183119.
[220] M.Y. Khalid, A. Al Rashid, Z.U. Arif, W. Ahmed, H. Arshad, Recent advances in nanocellulose-based different biomaterials: types, properties, and emerging applications, J. Mater. Res. Technol. 14 (2021) 2601–2623, https://doi.org/10.1016/j.jmrt.2021.07.128.
[221] A. Moudood, A. Rahman, A. Öchsner, M. Islam, G. Francucci, Flax fiber and its composites: an overview of water and moisture absorption impact on their performance, J. Reinf. Plast. Compos. 38 (2019) 323–339, https://doi.org/10.1177/0731684418818893.
[222] R.K. Gond, T.P. Naik, M.K. Gupta, I. Singh, Development and characterisation of sugarcane bagasse nanocellulose/PLA composites, Mater. Technol. 37 (2022) 2942–2954, https://doi.org/10.1080/10667857.2022.2088616.
[223] N.A.S. Aprilia, S. Mulyati, P.N. Alam, Karmila, A.C. Ambarita, Characterization nano crystalline cellulose from sugarcane baggase for reinforcement in polymer composites: effect of formic acid concentrations, IOP Conf. Ser. Mater. Sci. Eng. 345 (2018) 012033, https://doi.org/10.1088/1757-899X/345/1/012033.
[224] S.-Y. Lee, D.J. Mohan, I.-A. Kang, G.-H. Doh, S. Lee, S.O. Han, Nanocellulose reinforced PVA composite films: effects of acid treatment and filler loading, Fibers Polym. 10 (2009) 77–82, https://doi.org/10.1007/s12221-009-0077-x.
[225] S.S. Todkar, S.A. Patil, Review on mechanical properties evaluation of pineapple leaf fibre (PALF) reinforced polymer composites, Compos. B Eng. 174 (2019) 106927, https://doi.org/10.1016/j.compositesb.2019.106927.
[226] M. Mahardika, H. Abral, A. Kasim, S. Arief, M. Asrofi, Production of nanocellulose from pineapple leaf fibers via high-shear homogenization and ultrasonication, Fibers 6 (2018) 28, https://doi.org/10.3390/fib6020028.
[227] Fitriani, N.A.S. Aprilia, N. Arahman, Properties of nanocrystalline cellulose from pineapple crown leaf waste, IOP Conf. Ser. Mater. Sci. Eng. 796 (2020) 012007, https://doi.org/10.1088/1757-899X/796/1/012007.
[228] Z. Daud, M.Z. Mohd Hatta, A.S. Mohd Kassi, A. Mohd Aripi, Analysis of the chemical compositions and fiber morphology of pineapple (Ananas comosus) leaves in Malaysia, J. Appl. Sci. 14 (2014) 1355–1358, https://doi.org/10.3923/jas.2014.1355.1358.
[229] P. Nehra, R.P. Chauhan, Facile synthesis of nanocellulose from wheat straw as an agricultural waste, Iran. Polym. J. 31 (2022) 771–778, https://doi.org/10.1007/s13726-022-01040-0.
[230] R.C. do Lago, A.L.M. de Oliveira, A. de Amorim dos Santos, E.Z.M. Zitha, E.E. Nunes Carvalho, G.H.D. Tonoli, E.V. de Barros Vilas Boas, Addition of wheat straw nanofibrils to improve the mechanical and barrier properties of cassava starch–based bionanocomposites, Ind. Crop. Prod. 170 (2021) 113816, https://doi.org/10.1016/j.indcrop.2021.113816.
[231] J. Xu, E.F. Krietemeyer, V.M. Boddu, S.X. Liu, W.-C. Liu, Production and characterization of cellulose nanofibril (CNF) from agricultural waste corn stover, Carbohydr. Polym. 192 (2018) 202–207, https://doi.org/10.1016/j.carbpol.2018.03.017.
[232] H. Zhang, Y. Xu, S. Yu, Co-production of functional xylooligosaccharides and fermentable sugars from corncob with effective acetic acid prehydrolysis, Bioresour. Technol. 234 (2017) 343–349, https://doi.org/10.1016/j.biortech.2017.02.094.
[233] P. Chawla, K. Sridhar, A. Kumar, P.K. Sarangi, A. Bains, M. Sharma, Production of nanocellulose from corn husk for the development of antimicrobial biodegradable packaging film, Int. J. Biol. Macromol. 242 (2023) 124805, https://doi.org/10.1016/j.ijbiomac.2023.124805.
[234] R. Muthuraj, C. Lacoste, P. Lacroix, A. Bergeret, Sustainable thermal insulation biocomposites from rice husk, wheat husk, wood fibers and textile waste fibers: elaboration and performances evaluation, Ind. Crop. Prod. 135 (2019) 238–245, https://doi.org/10.1016/j.indcrop.2019.04.053.
[235] M.R. Mansor, M.J. Taufiq, A.F. Ab Ghani, Natural resources based green composite materials, in: Composite Materials: Applications in Engineering, Biomedicine and Food Science, Springer International Publishing, Cham, 2020, pp. 169–199, https://doi.org/10.1007/978-3-030-45489-0_7.
[236] H. Kargarzadeh, I. Ahmad, I. Abdullah, A. Dufresne, S.Y. Zainudin, R.M. Sheltami, Effects of hydrolysis conditions on the morphology, crystallinity, and thermal stability of cellulose nanocrystals extracted from kenaf bast fibers, Cellulose 19 (2012) 855–866, https://doi.org/10.1007/s10570-012-9684-6.
[237] J.R. Rajabathar, M. Sivachidambaram, J.J. Vijaya, H.A. Al-lohedan, D.M. D. Aldhayan, Flexible type symmetric supercapacitor electrode fabrication using phosphoric acid-activated carbon nanomaterials derived from cow dung for renewable energy applications, ACS Omega 5 (2020) 15028–15038, https://doi.org/10.1021/acsomega.0c00848.
[238] T.R. Harrison, V.K. Gupta, P. Alam, A.W. Perriman, F. Scarpa, V.K. Thakur, From trash to treasure: sourcing high-value, sustainable cellulosic materials from living bioreactor waste streams, Int. J. Biol. Macromol. 233 (2023) 123511, https://doi.org/10.1016/j.ijbiomac.2023.123511.
[239] K. Weiland, K. Alge, A. Mautner, A. Bauer, A. Bismarck, Horse manure as resource for biogas and nanolignocellulosic fibres, Bioresour. Technol. 372 (2023) 128688, https://doi.org/10.1016/j.biortech.2023.128688.
[240] V. Vilchez, E. Dieckmann, T. Tammelin, C. Cheeseman, K.-Y. Lee, Upcycling poultry feathers with (Nano)cellulose: sustainable composites derived from nonwoven whole feather preforms, ACS Sustain. Chem. Eng. 8 (2020) 14263–14267, https://doi.org/10.1021/acssuschemeng.0c04163.
[241] S. Cheng, K. Lau, T. Liu, Y. Zhao, P.-M. Lam, Y. Yin, Mechanical and thermal properties of chicken feather fiber/PLA green composites, Compos. B Eng. 40 (2009) 650–654, https://doi.org/10.1016/j.compositesb.2009.04.011.
[242] J. George, S.N. Sabapathi, Siddaramaiah, Water soluble polymer based hybrid nanocomposites, in: Hybrid Polymer Composite Materials, Elsevier, 2017, pp. 71–88, https://doi.org/10.1016/B978-0-08-100789-1.00003-4.
[243] D. Schiavi, R. Ronchetti, V. Di Lorenzo, R. Vivani, S. Giovagnoli, E. Camaioni, G. M. Balestra, Sustainable protocols for cellulose nanocrystals synthesis from tomato waste and their antimicrobial properties against pseudomonas syringae pv. tomato, Plants 12 (2023) 939, https://doi.org/10.3390/plants12040939.
[244] Z. Kassab, I. Kassem, H. Hannache, R. Bouhfid, A.E.K. Qaiss, M. El Achaby, Tomato plant residue as new renewable source for cellulose production: extraction of cellulose nanocrystals with different surface functionalities, Cellulose 27 (2020) 4287–4303, https://doi.org/10.1007/s10570-020-03097-7.
[245] T. Mahsuli, H. Suryanto, A. Larasati, M. Muhajir, Mechanical Properties of Bacterial Nanocellulose Membrane From Pineapple Peel Waste After Homogenization Process, 2019 050019, https://doi.org/10.1063/1.5115695.
[246] A.A.M. Moshi, D. Ravindran, S.R.S. Bharathi, S. Indran, S.S. Saravanakumar, Y. Liu, Characterization of a new cellulosic natural fiber extracted from the root of Ficus religiosa tree, Int. J. Biol. Macromol. 142 (2020) 212–221, https://doi.org/10.1016/j.ijbiomac.2019.09.094.
[247] J. Agarwal, S. Mohanty, S.K. Nayak, Valorization of pineapple peel waste and sisal fiber: study of cellulose nanocrystals on polypropylene nanocomposites, J. Appl. Polym. Sci. 137 (2020), https://doi.org/10.1002/app.49291.
[248] P.H.F. Pereira, V. Arantes, B. Pereira, H.L. Ornaghi, D.M. de Oliveira, S. H. Santagneli, M.O.H. Cioffi, Effect of the chemical treatment sequence on pineapple peel fiber: chemical composition and thermal degradation behavior, Cellulose 29 (2022) 8587–8598, https://doi.org/10.1007/s10570-022-04806-0.

[249] K.M.F. Hasan, P.G. Horváth, M. Bak, T. Alpár, A state-of-the-art review on coir fiber-reinforced biocomposites, RSC Adv. 11 (2021) 10548–10571, https://doi.org/10.1039/D1RA00231G.

[250] P.V. Subha, Anita Das Rabindranath, Synthesis of Nanocellulose from Coir Pith 28, CORD, 2012, p. 10, https://doi.org/10.37833/cord.v28i1.106.

[251] A. Ferrer, I. Filpponen, A. Rodríguez, J. Laine, O.J. Rojas, Valorization of residual empty palm fruit bunch fibers (EPFBF) by microfluidization: production of nanofibrillated cellulose and EPFBF nanopaper, Bioresour. Technol. 125 (2012) 249–255, https://doi.org/10.1016/j.biortech.2012.08.108.

[252] S.H. Ibrahim, S. W.K., A. Baharun, M.N.M. Nawi, R. Affandi, Thermal performance of oil palm fibre and paper pulp as the insulation materials, Sci. Technol. 5 (2014) 22–28, https://doi.org/10.33736/jcest.135.2014.

[253] M.K. Mohamad Haafiz, S.J. Eichhorn, A. Hassan, M. Jawaid, Isolation and characterization of microcrystalline cellulose from oil palm biomass residue, Carbohydr. Polym. 93 (2013) 628–634, https://doi.org/10.1016/j.carbpol.2013.01.035.

[254] T. Xu, H. Du, H. Liu, W. Liu, X. Zhang, C. Si, P. Liu, K. Zhang, Advanced nanocellulose-based composites for flexible functional energy storage devices (Adv. Mater. 48/2021), Adv. Mater. 33 (2021), https://doi.org/10.1002/adma.202170381.

[255] Z. Fang, B. Li, Y. Liu, J. Zhu, G. Li, G. Hou, J. Zhou, X. Qiu, Critical role of degree of polymerization of cellulose in super-strong nanocellulose films, Matter 2 (2020) 1000–1014, https://doi.org/10.1016/j.matt.2020.01.016.

[256] B. Thomas, M.C. Raj, A.K. Ba, R.M. Ha, J. Joy, A. Moores, G.L. Drisko, C. Sanchez, Nanocellulose, a versatile green platform: from biosources to materials and their applications, Chem. Rev. 118 (2018) 11575–11625, https://doi.org/10.1021/acs.chemrev.7b00627.

[257] X. Chen, W. Yu, L. Ma, S. Zhou, X. Liu, Mechanical properties and thermal characteristics of different-density phenolic foams, J. Therm. Anal. Calorim. 144 (2021) 393–401, https://doi.org/10.1007/s10973-020-10361-2.

[258] K. Mohammed, D. Yu, A.A. Mahdi, L. Zhang, M. Obadi, W. Al-Ansi, W. Xia, Influence of cellulose viscosity on the physical, mechanical, and barrier properties of the chitosan-based films, Int. J. Biol. Macromol. 259 (2024) 129383, https://doi.org/10.1016/j.ijbiomac.2024.129383.

[259] C. Wu, S. Egawa, T. Kanno, H. Kurita, Z. Wang, E. Iida, F. Narita, Nanocellulose reinforced silkworm silk fibers for application to biodegradable polymers, Mater. Des. 202 (2021) 109537, https://doi.org/10.1016/j.matdes.2021.109537.

[260] B. Mazela, K. Tomkowiak, D. Jones, Strength and moisture-related properties of filter paper coated with nanocellulose, Coatings 12 (2022) 1376, https://doi.org/10.3390/coatings12101376.

[261] D. Barnat-Hunek, M. Grzegorczyk-Frańczak, M. Szymańska-Chargot, G. Łagód, Effect of eco-friendly cellulose nanocrystals on physical properties of cement mortars, Polymers (Basel) 11 (2019) 2088, https://doi.org/10.3390/polym11122088.

[262] R.J. Moon, A. Martini, J. Nairn, J. Simonsen, J. Youngblood, Cellulose nanomaterials review: structure, properties and nanocomposites, Chem. Soc. Rev. 40 (2011) 3941, https://doi.org/10.1039/c0cs00108b.

[263] G. Yu, H. Yang, D. Luo, X. Cheng, M.K. Ansah, A review on developments and researches of building integrated photovoltaic (BIPV) windows and shading blinds, Renew. Sust. Energ. Rev. 149 (2021) 111355, https://doi.org/10.1016/j.rser.2021.111355.

[264] S. Torgbo, P. Sukyai, Biodegradation and thermal stability of bacterial cellulose as biomaterial: the relevance in biomedical applications, Polym. Degrad. Stab. 179 (2020), https://doi.org/10.1016/j.polymdegradstab. 2020.109232.

[265] K. Kuperkar, L.I. Atanase, A. Bahadur, I.C. Crivei, P. Bahadur, Degradable polymeric bio(nano)materials and their biomedical applications: a comprehensive overview and recent updates, Polymers (Basel) 16 (2024), https://doi.org/10.3390/polym16020206.

[266] M. Kim, H. Doh, Upcycling food by-products: characteristics and applications of nanocellulose, Chem. Asian J. 19 (2024), https://doi.org/10.1002/asia.202301068.

[267] H. Rana, A. Sharma, S. Dutta, S. Goswami, Recent approaches on the application of agro waste derived biocomposites as green support matrix for enzyme immobilization, J. Polym. Environ. 30 (2022) 4936–4960, https://doi.org/10.1007/s10924-022-02574-3.

[268] C.K.S. Pillai, W. Paul, C.P. Sharma, Chitin and chitosan polymers: chemistry, solubility and fiber formation, Progr. Polym. Sci. (Oxford) 34 (2009) 641–678, https://doi.org/10.1016/j.progpolymsci.2009.04.001.

[269] B. Prathab, T.M. Aminabhavi, Molecular modeling study on surface, thermal, mechanical and gas diffusion properties of chitosan, J. Polym. Sci. B Polym. Phys. 45 (2007) 1260–1270, https://doi.org/10.1002/polb.21109.

[270] J.J.G. Van Soest, J.F.G. Vliegenthart, Crystallinity in Starch Plastics: Consequences for Material Properties, 1997.

[271] S. Thymi, M.K. Krokida, A. Pappa, Z.B. Maroulis, Structural properties of extruded corn starch, J. Food Eng. 68 (2005) 519–526, https://doi.org/10.1016/j.jfoodeng.2004.07.002.

[272] J.C. Bénézet, A. Stanojlovic-Davidovic, A. Bergeret, L. Ferry, A. Crespy, Mechanical and physical properties of expanded starch, reinforced by natural fibres, Ind. Crop. Prod. 37 (2012) 435–440, https://doi.org/10.1016/j.indcrop.2011.07.001.

[273] R.A. Auras, B. Harte, S. Selke, R. Hernandez, Mechanical, physical, and barrier properties of poly(lactide) films, J. Plastic Film Sheeting 19 (2003) 123–135, https://doi.org/10.1177/8756087903039702.

[274] B.H. Tan, J.K. Muiruri, Z. Li, C. He, Recent progress in using stereocomplexation for enhancement of thermal and mechanical property of polylactide, ACS Sustain. Chem. Eng. 4 (2016) 5370–5391, https://doi.org/10.1021/acssuschemeng.6b01713.

[275] E. Bugnicourt, P. Cinelli, A. Lazzeri, V. Alvarez, Polyhydroxyalkanoate (PHA): review of synthesis, characteristics, processing and potential applications in packaging, Express Polym Lett 8 (2014) 791–808, https://doi.org/10.3144/expresspolymlett.2014.82.