In the Field

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Nanocellulose industrial uptake after the hype

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Abstract: Nanocellulose, a renewable and abundant bionanomaterial with exceptional physical, chemical, and biological properties, is a very promising functional material. Its potential applications, including composites, biomedical products, membranes, electrodes, supercapacitors, and flexible electronics, have been limited by high production costs. This study evaluates the industrial adoption of nanocellulose following the peak of the technology hype cycle, focusing on efforts to commercialize lower-cost production routes. The study also highlights the primary advanced applications, beyond biomedical products, in which nanocellulose is increasingly adopted by industry. The results are relevant not only to researchers in chemistry, materials science, biotechnology, and engineering, but also to professionals in the bioeconomy sector. © 2026 Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: nanocellulose; CytroCell; cellulose nanofiber; cellulose nanocrystal; bacterial nanocellulose; carbon fiber; bioeconomy

Introduction

Nanocellulose is a bionanomaterial with outstanding physical, chemical, and biological properties. It is lightweight, has exceptional mechanical strength and high thermal stability, exhibits a high aspect ratio and surface area, and is biodegradable, biocompatible, renewable, and, in principle, abundant. It is therefore a very promising functional material with potential applications in composites, biomedicine, membranes, electrodes, supercapacitors, and flexible electronics.[1]

The material is generally sourced from wood pulp via mechanical disintegration in water (microfibrillated cellulose), chemical or enzymatic pretreatment followed by disintegration in water to yield cellulose nanocrystals (CNC) or cellulose nanofibers (CNF), or microbial synthesis to produce bacterial nanocellulose (BC).[2]

In further detail, CNC is obtained via acid hydrolysis of cellulose with sulfuric acid; CNF via partial chemical or enzyme-assisted modification of cellulose fibers followed by mechanical disintegration of the partly derivatized fibers; and BC from glucose using *Gluconoacetobacter xylinus* bacteria.

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In general, these processes are either inefficient, such as in the case of BC synthetic process,[3] or generate large quantities of toxic effluents due to the use (or formation) of harmful chemical reactants (mineral acid, hypochlorite, ammonia, etc.). High selling prices result from high production costs, due both to the capital cost of industrial homogenizers and microfluidizers (between $500 000 and $2 million), and to the energy-intensive cellulose fibrillation process involving homogenization and microfluidization and requiring either chemical (carboxylation or phosphorylation) or enzymatic treatment to reduce the otherwise prohibitive energy demand of 20 000–30 000 kWh per t for pure cellulose fibrillation.[4]

The first small-scale CNC and CNF chemical production plants (a few hundred t per year) started operation in Canada[5] in 2011 and in Japan in 2017.[6] The Canadian facility halted production shortly afterwards, but resumed CNC production in 2019 at its newly modernized facility employing a '50% more efficient process'.[5]

The biomaterial was discovered in 1977 at a large paper and pulpwood company in the USA and was termed 'microfibrillated cellulose' by Turbak.[7] For nearly 50 years, market research studies have forecast rapid market growth and large-scale industrial uptake of nanocellulose across multiple industrial products and markets.

Such growth, however, never materialized,[8] whereas hype persisted in the context of broader nanotechnology hype.[9] Analysis of this cycle has recently led us to suggest that realization of the industrial potential of nanocellulose would benefit from the principal lesson of the hype phase, namely that high production costs hindered industrial uptake.[8]

Large-scale production and adoption therefore requires the development of green and substantially more efficient production processes that reduce both capital and operating costs.[10]

As noted in 2017 by entrepreneurs and materials science researchers who founded a company developing innovative Li-ion battery technologies based on nanostructured materials, 'for startups and venture capitalists, the word "nanotechnology" evokes commercial failure'.[11] With the dissipation of nanotechnology hype and the withdrawal of venture capital from nanotechnology ventures since the early 2010s, this study provides an overview of practical developments in nanocellulose following the conclusion of the hype cycle.

The material continues to penetrate low-volume, high-value markets, such as the biomedical product segment, where BC first found application, exemplified by the XCell nanocellulose, commercialized worldwide by a large pharmaceutical company for surgical wound healing.[12] In early 2025, for example, a company in Finland commercialized a nanocellulose-based hydrogel for soft tissue repair and orthopedic applications, which is easy to inject, even at high levels of stiffness, due to its shear thinning properties.[13]

These developments are in line with guidelines for successful biobased production, which recommend that bioeconomy companies should first target high-value applications and bioproducts rather than low-value applications such as bioplastics intended to replace synthetic polymers used in food packaging.[14] The high price of pharmaceutical-grade nanocellulose enables the costs of current industrial production routes, including BC, to be absorbed.

For nanocellulose to enter large-volume ('commodity') product markets such as packaging, construction materials, and consumer goods successfully, however, its price (> $20 per kg in 2023)[15] must be reduced to $2–3 per kg.

Following a brief analysis of recent developments in nanocellulose science and technology research, this study investigates the current status of attempts to commercialize lower cost nanocellulose production routes, and the first advanced industrial applications beyond biomedical products.

The results of the study may be relevant for bioeconomy industry professionals, including managers and entrepreneurs within bioeconomy companies, in addition to researchers in chemistry, engineering, materials science, and biotechnology.

Results and discussion

Research landscape in nanocellulose science and technology

Research in the field of nanocellulose is a 'hot topic' in today's scientific research conducted worldwide.

In 2024 the number of original research articles written in English published in peer reviewed journals that were indexed by a proprietary research database reached the highest level ever, with nearly 1806 original research articles published in just 1 year (Fig. 1).[16] For comparison, the number of original research articles published in 2014 was 184, translating into a nearly tenfold increase in just one decade.

The bar graph in Fig. 2 shows that China is now by far the world's largest contributor to innovation in the field of nanocellulose.

The presence of India (3rd), Brazil (8th), and Malaysia (10th) in the top ten country ranking clearly shows that countries in the so-called 'Global South' are interested in commencing nanocellulose production.

The ranking of countries hosting the world's largest paper and cellulose pulp companies (China, Canada, the USA, Sweden, Finland, and Japan) highlights the strong interest of the paper and pulp industry in identifying new commercial

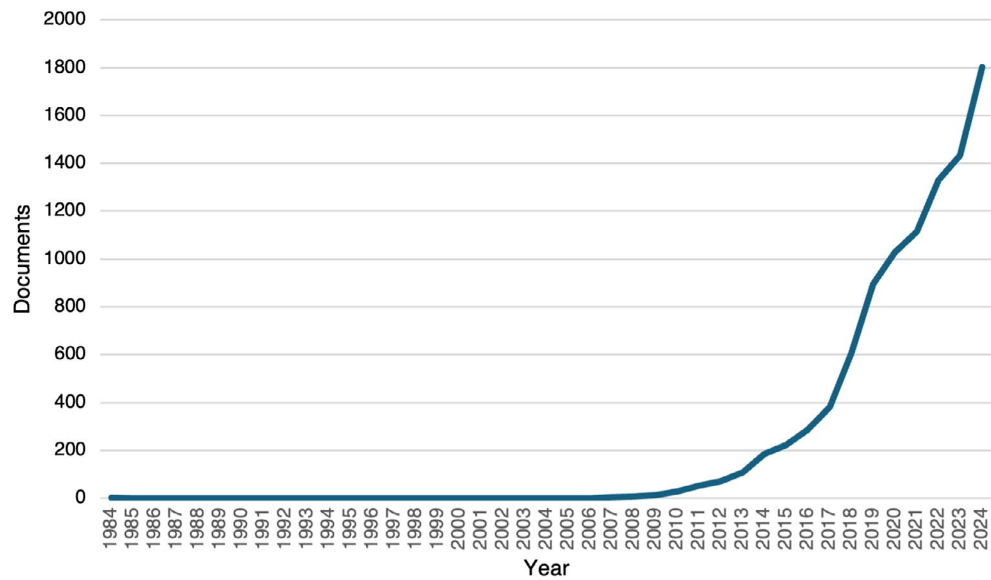

Figure 1. Original research articles, in English, in research journals indexed by Scopus by year containing 'nanocellulose' in the title, abstract or keywords (1984–2024). *Source*: Scopus, 2025.

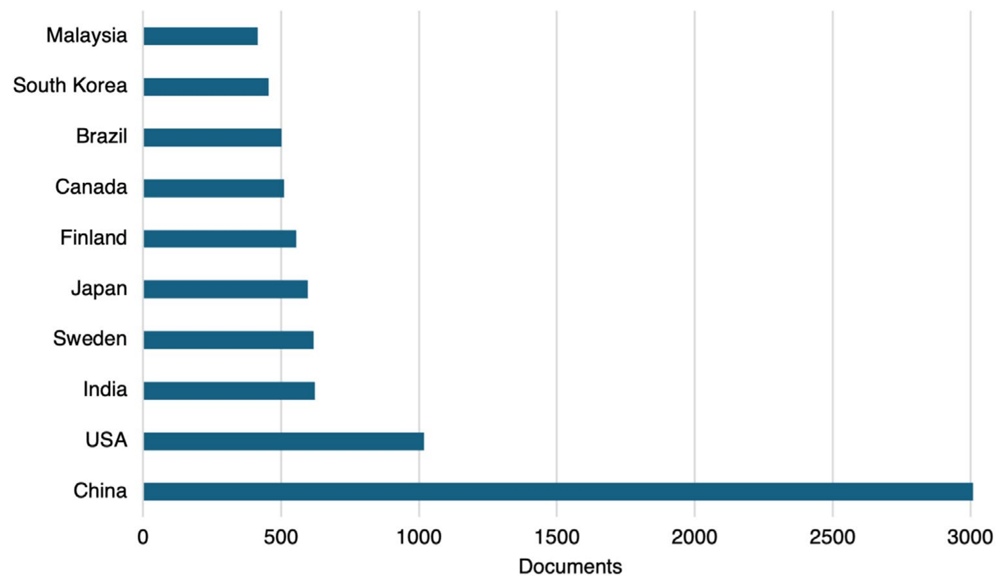

Figure 2. Top ten countries by number of original research articles in Scopus-indexed journals (1984–2024) containing 'nanocellulose' in the title, abstract, or keywords. *Source*: Scopus, 2025.

outlets for its core product, wood cellulose pulp used in paper and paperboard production, in response to the dramatic decline in demand for newsprint and printing and writing papers driven by the advent of the Internet.[17]

Research into nanocellulose remains strong in the USA, where a large (wood) pulp and paper industry continued to exist during the deindustrialization period of the second great globalization (1990–2020).

Despite a substantial decline in production, which peaked in 1999, the USA remained the second-largest producer of paper and paperboard worldwide in 2023, and a net exporter of both products.[18]

Recognizing that nanocellulose price reduction requires greener production routes, academic researchers have increasingly focused on developing such new processes. For instance, the number of original research articles on sustainable nanocellulose production has risen markedly since 2020 (Fig. 3).

These research articles describe a wide range of approaches, from the use of enhanced enzymes to subcritical water.

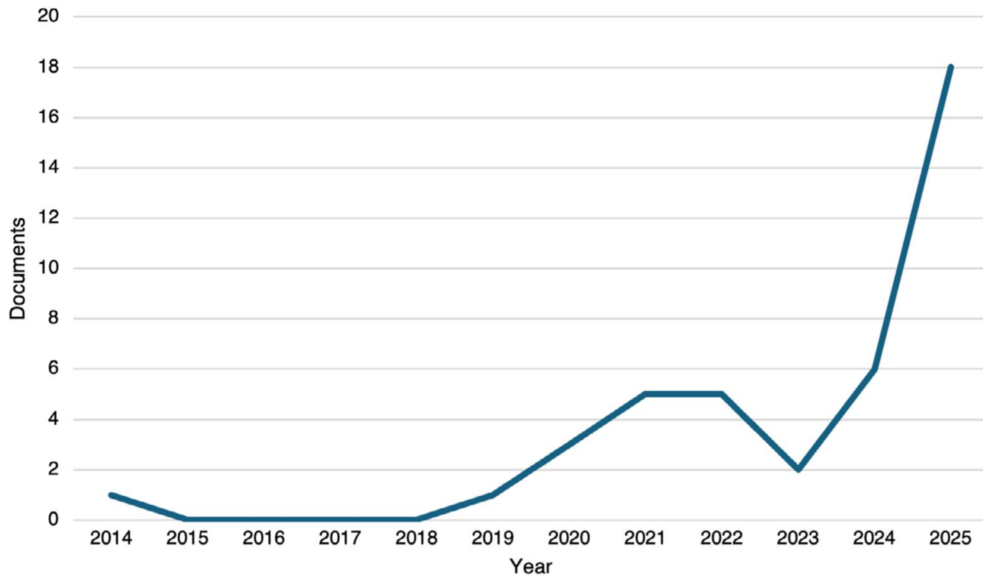

Figure 3. Original research articles, in English, published in Scopus-indexed journals by year (1984–2025) containing ‘nanocellulose’ and/or ‘sustainable production’ in the title, abstract, or keywords. *Source*: Scopus, 2025.

Industrial chemical companies, however, usually do not publish the outcomes of industrial research in scientific journals.

They do, however, disclose these findings in patent applications. A search of the World Intellectual Property Organization (WIPO) patent database for patents including the English phrase ‘production of nanocellulose’ in the front page yielded 57 patents.[19]

Inspection of these patents shows a clear progression. The first, granted in 2013 to the Indian Council of Agricultural Research, describes enzymatic hydrolysis of microcrystalline cellulose in an ultrafiltration membrane-based bioreactor, enabling semi-continuous nanocellulose production with minimal effluents and low energy consumption.[20] More recent patents include processes that reduce overall energy use in nanocellulose production by at least 50% by first dissolving cellulose in a swelling solution of morpholine or piperidine, followed by high-shear or high-pressure treatment in a homogenizer, such as a microfluidizer.[21]

Many other new nanocellulose production routes have been introduced, including green methods that avoid toxic effluents and offer significant applicative potential.[10] This study therefore investigated the current status of efforts to commercialize lower cost nanocellulose production routes.

New production processes, new plants, new raw materials

In late 2024 a company conducted the first nanocellulose production campaign at a chemical plant in South Carolina, USA, using the nitro oxidation process (NOP), a closed-loop, effluent-free method for producing carboxylated cellulose nanofibers and a biofertilizer directly from raw jute feedstock.[22]

Developed by Hsiao’s team, this one-pot method uses a mixture of aqueous nitric acid (HNO_3, 30% to 50%, depending on the substrate) and catalytic amounts of potassium nitrite (KNO_2) to generate, *in situ*, the nitrosonium ion (NO^+) responsible for cellulose primary alcohol groups oxidation to carboxylic acid, while simultaneously partly removing lignin and hemicellulose from the treated biomass.[23] In the case of sugarcane bagasse, for example, the process employs nitric acid at 50% concentration with a 10:1 acid-to-biomass ratio at 50 °C for 5 h, producing carboxylated nanocellulose with a high carboxyl content (1.2 mmol g^{-1}), which facilitates mechanical defibrillation into nanoscale fibers using high-pressure homogenization.

The production process at the chemical plant was conducted in a closed vessel under a modest 5 bar pressure. This pressure dramatically increases the CNF degree of oxidation to over 3 mmol g^{-1}.[24]

The solid product is a lignin-rich CNF that can be used effectively to produce a hydrogel (1 g of powder yielding 98 g hydrogel) suitable for numerous agricultural applications (soil amendment, hydro-seeding, hydroponic agriculture, reverse desertification processes). The potassium- and nitrogen-rich liquid acidic effluent is neutralized with solid KOH and used as a liquid fertilizer, providing readily bioavailable nitrogen

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and organic carbon. The two-step process can employ a wide range of biowastes, including agriculture waste, food waste, brewery byproducts, and cattle farming waste.

No alkali treatment or bleaching is required to purify cellulose from lignocellulosic feedstocks, unlike in current industrial CNF and CNC production processes. Combined with its ability to process diverse raw biomass, the low energy and water requirements and absence of toxic effluents make this process suitable for large-scale adoption, even using existing chemical plants.

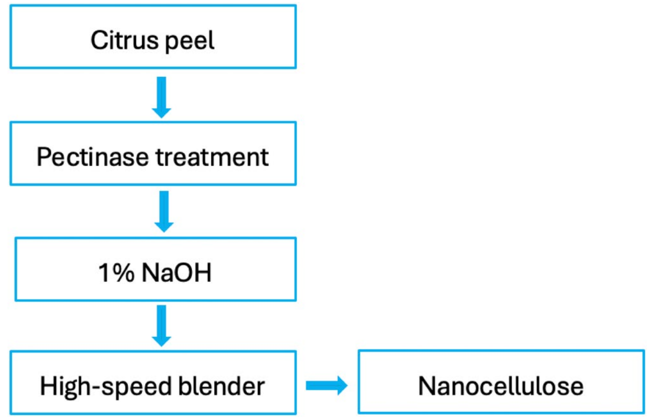
In 2023, Sothornvit and co-workers in Thailand reported the successful, high-yield (24%) synthesis of pure nanocellulose from abundant and virtually free rice husk using high-pressure homogenization.[25] The only chemical reagents used were environmentally friendly aqueous NaOH (10% w/v) and aqueous H_2O_2 (35% w/v), used to remove lignin, hemicellulose, and silica, and to bleach the delignified husk, respectively. The resulting cellulose dispersed in pure water at 1 wt%, is homogenized in a high-pressure homogenizer at 120 MPa for up to 12 cycles, followed by sonication in an ultrasonic bath at 150 W for 30 min.

As demonstrated by researchers in Thailand, using freely available rice husk instead of substantially more expensive bleached wood pulp as nanocellulose feedstock combined with a process that significantly reduces water effluent treatment costs provides a practical route to lower production costs. The alkaline solution can be neutralized easily with acid to yield a pure salt that can be recovered and sold, whereas unreacted hydrogen peroxide decomposes readily into water and oxygen.

By late 2025, a South Korean company, established in 2017, completed construction of a nanocellulose production plant in Pohang capable of producing more than 1000 t per year.[26] The nanocellulose, sourced from rice husks, is produced via a proprietary process. Targeted markets include binder and separator materials for Li-ion batteries, replacing poly(vinylidene fluoride) cast in toxic *N*-methyl-2-pyrrolidone (NMP) with the nanocellulose technology licensed by Inha University,[27] as well as biomedical applications, including medical-grade nanocellulose for extracellular matrix materials supporting cell and organoid growth.

Similarly, in 2021, a company in Japan's Ehime Prefecture commercialized citrus peel CNF based on research initiated in 2015 by Hideno's team at Ehime University.[19] The team found that, compared with wood pulp, also commonly used in Japan as raw material for CNF, the cellulose fibers contained in citrus peels were finer and more easily nanofibrillated through a green and rapid process (Scheme 1).

In brief, waste orange peel is first treated with pectinase overnight at 48 °C to remove pectin. This is followed by simple treatment with 1 wt% NaOH solution in an autoclave at 121 °C for 1 h. A 1 wt% dispersion of the resulting purified cellulose filtrate is then fibrillated in water using a high-speed blender to produce a nanocellulose suspension.[28]



Scheme 1. Preparation of cellulose nanofibers (CNF) from orange peel developed by Hideno and co-workers. Adapted with kind permission from Hideno, A, Revitalizing local industry with nanofibers made from biomass in Ehime. Ehime University, 23 September 2023. Available: https://www.ehime-u.ac.jp/en/data_study/revitalizing-local-industry-with-nanofibers-made-from-biomass-in-ehime/ [6 October].

Compared with wood pulp CNF, citrus CNF retains oily substances as substantially smaller droplets in water, which remain stable for longer periods than those in CNF derived from hardwood pulp.[29] Initially used as an emulsion stabilizer by a cosmetic company to produce creams with reduced stickiness,[19] this property is now exploited in the food industry, including by a company in Japan that commercializes a canned mandarin-based cocktail with enhanced flavor and aroma, achieved by emulsifying orange essential oil with citrus CNF.[30]

Containing a negligible amount of lignin and overly abundant in citrus fruit growing countries, waste citrus peel (orange, lemon, and grapefruit) from industrial juice production is ideally suited for low-cost nanocellulose manufacture compared with wood pulp.[31]

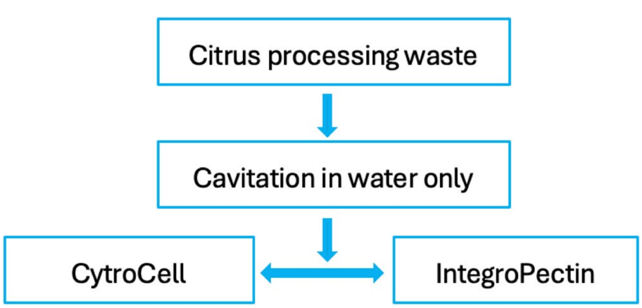
The CytroCav process, developed in Italy, converts industrial citrus processing waste (CPW) into highly esterified CytroCell nanocellulose and bioactive IntegroPectin (Scheme 2).[32] This process requires no added chemicals: citric acid naturally present in CPW promotes esterification of the cellulose fibrils during acoustic or hydrodynamic cavitation, and the implosion of the cavitation bubbles drives extensive fibrillation at a fraction of the energy cost of conventional mechanical treatments.

The unique properties of this nanocellulose – low crystallinity, high surface charge density, and easy dispersion in water or green aprotic organic solvents[33] – enable its use as a high-value additive, ranging from use in construction materials, such as air lime carbonation accelerators that improve the mechanical properties and durability of lime mortars,[34] to use in advanced polymer composite membranes for electrochemical applications.[35,36]

Another way to reduce the cost of CNF manufacturing is by the introduction of phosphate groups by treatment of cellulose with diammonium phosphate/urea (cellulose:DAP:urea in molar ratios of 1:1:1) at 150 °C. Urea inhibits the acid hydrolysis of cellulose due to protons released by $NH_4H_2PO_4$ and acts as a phosphorylation catalyst.

In 2017, a pilot facility producing CNF using phosphorylation began operation of a pulp and paper company at the Tomioka Mill in Japan.[37] The company produces high-quality CNF, characterized by high transparency, viscosity, and thixotropy, at substantially lower cost than the conventional TEMPO-mediated oxidation of kraft pulp, which oxidizes cellulose primary alcohol groups using NaOCl with a catalytic amount of bromide.[38]

Phosphorylation disrupts hydrogen bonding and promotes intermolecular expansion, driving water adsorption, and fiber swelling, while reducing energy consumption by 42% compared with mechanical fibrillation of cellulose oxidized via conventional TEMPO-mediated carboxylation.[39]



Scheme 2. The CytroCav process affording CytroCell nanocellulose and IntegroPectin flavonoid-pectin conjugate from citrus processing waste.

At EXPO 2025, the company, producing both transparent and coarse phosphorylated CNF slurries, presented a proton-conducting nanocellulose membrane for hydrogen fuel cells as a sustainable alternative to conventional perfluorosulfonic acid (PFSA) membranes.[40] Nanocellulose membranes offer enhanced gas barrier and mechanical properties while maintaining proton conductivity comparable with PFSA membranes.

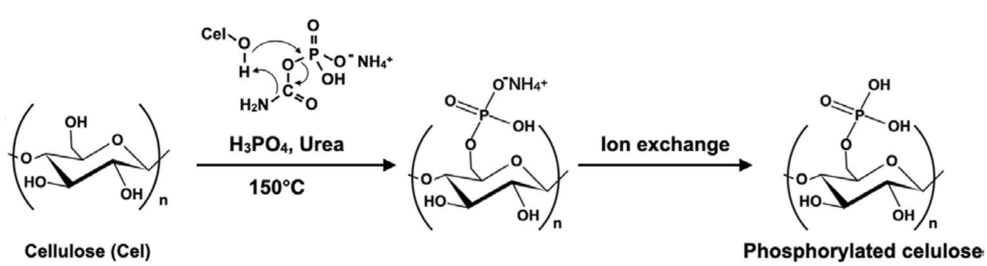
For example, a phosphorylated CNF membrane readily obtained following ion exchange with protons (Scheme 3) and casting from an aqueous dispersion has a maximum proton conductivity of 1.2×10^{-1} S cm^{-1} at 80 °C and 95% RH, comparable with that of Nafion 212 measured under the same conditions.[41]

The outcome is due to the formation of a dense network structure between the nanofibers, creating continuous long-range proton conductive channels. High mechanical strength is due to cross-linking between the nanofibers.

Similarly, in late 2025, another paper company producing its own CNF began manufacturing a CNF composite resin with an annual production capacity of 2000 t. Dubbed 'ELLEX-R67', the resin is a high-concentration pellet containing 67% CNF (carbamate cellulose) and 33% polypropylene–urea blend to improve compatibility, providing customer companies with flexibility in resin design due to easy molding.[42] The composite's improved rigidity allows for thinner components, reducing weight and plastic use, whereas its enhanced mechanical properties make it well suited for automotive applications.

The company produces CNF via phosphite esterification of cellulose using $H(NH_4)PO_3$/urea/water to form $OP(=O)O^-$, which is then substituted with a carbamate group by reaction with urea.[43]

When heated, urea is decomposed into isocyanic acid and ammonia (Eqn 1). Isocyanic acid is very reactive, and reacts with a hydroxyl group of cellulose forming a carbamate (Eqn 2):



Scheme 3. Phosphorylation and ion exchange process to produce phosphorylated CNF. Adapted with kind permission from Matsuo Y, Kimura T, Koyanagi H, Netsu N, Komatsu F, Nagata T, Nishitsuji S, Matsui J, Masuhara A Phosphorylated cellulose nanofiber membranes with high proton conductivity for polymer electrolyte membranes. Green Chem 27:3532–3541 (2025). https://doi.org/10.1039/d4gc05347h.

$$NH_2 - CO - NH_2 \rightarrow HN = C = O + NH_3 \quad (1)$$

$$Cell - OH + H - N = C = O \rightarrow Cell - O = C - NH_2 \quad (2)$$

After mechanical fibrillation by disintegration in water, the process affords high quality CNF made available to customers in three forms: aqueous dispersion, powder, and molded sheets. Its mechanical and physical properties are far superior to those of plastic materials.[44]

Replacement of glass and carbon fiber in composites

Carbon fiber (CF) composites currently dominate the market for high-performance, lightweight materials. Nanocellulose nevertheless has the potential to replace CF in many composite materials. Carbon-fiber-reinforced polymer matrix composites are widely used in aerospace, automotive, wind power, construction, rail, communication, and medical equipment, with global demand rising rapidly to 333 000 t in 2025.[45]

Compared with CF, nanocellulose offers superior mechanical properties and lower weight.[46] As also noted by Jiang and co-workers, composite structures based on microfibers assembled from CNFs provide a huge 'design space' spanning nanometer- to meter-length scales, enabling effective exploitation of the exceptional properties of nanocellulose fibers.[46]

Moisture sensitivity and interfacial compatibility between hydrophilic cellulose and hydrophobic polymers, which historically limited the performance of nanocellulose composites relative to CF-based materials,[47] has now been resolved.

Incorporating a hydrophobic species, such as indigo dye present in cotton waste fibers, is sufficient to produce cellulose nanofibers suitable for reinforced polymer composites with markedly enhanced tensile and flexural strength and moduli. For instance, when 30% fibers from bleached white and indigo-dyed denim fabrics were introduced, the tensile moduli of the resultant composites reached 4.57 and 4.59 GPa, respectively, compared with 1.60 GPa for neat polypropylene.[48] The hydrophobic indigo dye improves interfacial bonding between cotton fibers and the polymer matrix, and low water uptake of the composites further indicates strong filler/matrix adhesion.

When appropriately formulated with hydrophobic species, nanocellulose will compete successfully with CF only when its price falls below that of CF. At that point, nanocellulose would have addressed the significant environmental and economic challenges associated with the disposal and recycling of carbon fiber composite waste, which arise from the three-dimensional, interconnected network of carbon and graphite that renders these materials insoluble in organic solvents and non-biodegradable.[49]

Carbon fiber, predominantly derived from polyacrylonitrile (PAN), which accounts for more than 53% of total production costs,[50] remains expensive, with prices approaching those of nanocellulose. For example, in 2023, prices were approximately €20 per kg for CNF and €18 per kg for carbon fiber.[51] Evidence of a continuing decline is provided by the average CNF selling price of $50 per kg reported in 2018.[52]

Indeed, a European carmaker recently started to use nanocellulose-reinforced plastics, resulting in a 15% vehicle weight reduction, contributing to both improved fuel efficiency and enhanced mechanical properties of the vehicle.[53]

To meet customer demand for efficient product delivery, nanocellulose companies have recently developed methods to replace dilute dispersions, typically 1% to 3% for CNF and 1% to 10% for CNC, which initially dominated the market, with stable dried powders that avoid irreversible aggregation and the associated logistical and processing inefficiencies.[54] Dewatering nanocellulose suspensions is inherently challenging because of their high water-holding capacity and viscosity, even at low concentrations. This issue can be addressed by adding a dispersing agent that prevents irreversible agglomeration during drying. The dispersion agent incorporates nanocellulose into a composite product and readily releases individual nanocellulose particles during subsequent composite formulation.

In a recent review of techno-economic analysis (TEA) studies of nanocellulose production routes, academic researchers based in India concluded that 'many TEA models still operate in isolation from realistic market dynamics and product performance criteria'.[55]

Rather than focusing on claims made by other researchers, including those in industry, regarding the economics of chemical products and technologies, academic researchers in chemistry and the bioeconomy may learn more from actual industrial practice. Prices for different forms of nanocellulose between 2018 and 2025, summarized in Table 1, indicate that industry is actually progressing towards substantially lower selling prices and, consequently, further reductions

Table 1. Price for different nanocelluloses and information source.

Nanocellulose	Price	References
Cellulose nanofiber (CNF)	€20 per kg in 2023 ($50 per kg in 2018)	[51,52]
Cellulose nanocrystal (CNC)	$50 per kg in 2025	[56]
Bacterial nanocellulose (BC)	$50 per g in 2021	[57]

in production costs. Overly expensive BC is therefore likely to remain confined to biomedical applications until new approaches, such as the use of Eucalyptus bark hydrolysate as a production medium yielding a 40-fold increase in BC output compared with standard media,[58] are successfully commercialized.

Conclusions

This analysis of efforts to commercialize lower cost nanocellulose production routes following the end of the technology hype cycle reveals a number of relevant findings.

First, several new companies based in different regions of the world are approaching commercialization of these production routes. To reduce production costs further, these processes increasingly rely on low-cost feedstocks such as biowaste, including rice husk, jute residues, and citrus-processing waste, rather than expensive wood pulp.

The analysis also shows that the price of conventionally made nanocellulose, particularly CNF, has declined substantially over the last 5 years, decreasing from $50 per kg in 2018 to just over $20 in 2023.

Coupled with technical innovations that have resolved moisture sensitivity and compatibility issues between hydrophilic cellulose and hydrophobic polymers, these initial reductions in production costs and selling prices have enabled nanocellulose to enter the polymer composites market and begin replacing carbon fiber. This transition has started in the largest mobility segment, automotive manufacturing, and is expected to extend progressively to other major carbon fiber composite applications within the mobility sector.

The entry of nanocellulose into other high-value market segments, such as flexible displays and water filtration membranes, is now feasible and is expected to progress steadily. Films based on cellulose nanofibers exhibit excellent thermal dimensional stability due to their low coefficient of thermal expansion, a key requirement for electronic applications.

Substantial further reductions in production cost and selling prices to the $2–3 per kg required for entry into the packaging and other commodity markets will require the replacement of conventional production routes – based on chemical or enzymatic pretreatment followed by mechanical fibrillation – with completely new methods such as cavitation, and substituting expensive wood pulp with low-cost biowaste cellulose.

In conclusion, considering the ubiquity of cellulose in the natural environment, the large-scale production of nanocellulose is expected to materialize rapidly when economically viable production processes are established at industrial level, both in economically developing countries accessing huge biomass and agroindustrial resources, such as Brazil, India, or Russia, and in countries seeking reindustrialization, such as the USA or many European countries.

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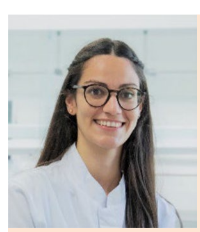

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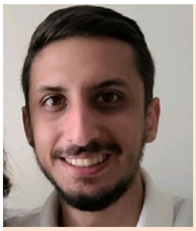

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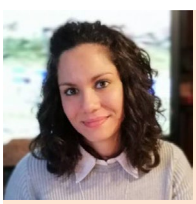

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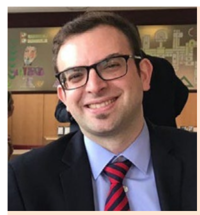

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