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Review: The Importance, Structure, Properties, and Applications of Cellulose and Nanocellulose

R. Sh. Mahmood [(1)], **Y. T. Mahmood** [(2*)]

[1]Department of Chemistry, College of Science, Mustansiriyah University, Baghdad, Iraq
[2]Department of Chemistry, College of Education for Pure Science, University of Mosul.

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Correspondence:
Younis Turki Mahmood
younsturkian@uomosul.edu.iq

Abstract

In the past few years, cellulose fibres have reached great importance in our lives, as they are the main component of plant fibres and are characterized by their lightweight and durability, in addition to being non-toxic and considered friendly to humans and the environment. Hydroxyl groups are considered to be the effective groups in the composition of cellulose, as the presence of these groups opens wide horizons for the uses of cellulose through the chemical responses that can grow through these groups when the appropriate conditions are available for the reaction.

At the same time, it is clear that laboratory performance does not automatically translate into industrial feasibility. While the scientific literature strongly emphasizes enhanced material properties, discussions about production cost, process integration, and long-term economic sustainability are comparatively limited. Therefore, we will first address a simplified explanation about cellulose, its organization, and its typical properties; and then we will discuss a simplified explanation of Nanocellulose, its qualities, its unique properties, its principal sources, and its innovation and advanced applications.

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1. Introduction

The use of materials from nature, "green" recycled and sustainable materials, has become very important in the development of various highly efficient goods that have a low environmental impact [1].

This fieldwork has drawn the interest of a vast number of scientists because such resources may be a solution to the continuously draining non - renewable materials, air pollution, energy shortage, and global warming [2].

Chitin, Chitosan, gelatin, cellulose, starch, and alginate are successful candidate under these conditions, depending on the availability of different resources [3].

Cellulose is the most important material in nature, the extraction of which from the biosphere is very simple and can be found in tree branches, moss, and other microorganisms [4].

This abundant natural polymer, which looks like an inexhaustible source of mineral materials, can be altered and used for many industrial uses available, and there is still a lot to be learned about cellulose [5].

Once cellulose chains are joined together, the utility of cellulose can be tremendous, rendering the regions very organized, and can be separated as nanoparticles, classified as nano celluloses or cellulose nanomaterials, which according to their physicochemical tend to be a useful form of materials Properties, They are also reusable and plentiful, collecting between chemical inertia and excellent rigidity, low density, low thermal expansion coefficient, high strength, ability to modify surface chemistry and dimensional stability [6].

Nano-cellulose can be divided into two main types:

1. nanofibers (cellulose nanofibrils, cellulose nanocrystals, and bacterial cellulose).

2. nanostructured materials (cellulose microcrystals and cellulose microfibrils)[7].

The size and morphology of each form of nano-cellulose depend on the source of cellulose, the isolation, and processing conditions. Nano cellulose, which can currently be manufactured, can be used in many fields such as wood adhesives, batteries, cosmetics, nanocomposite materials, food coatings, biomedical products, supercapacitors, catalytic supports, electronic part models, electroactive polymers, continuous fabrics and textiles, antimicrobial films, paper goods, and cement[8,9,10].

In this article, we explain some of the latest applications of nanocellulose (NC), specific cellulose nanocrystals (CNC), as well as the related interest surrounding its production and new directions.

2. Review Methodology

The present review is based on a structured survey of peer-reviewed articles retrieved primarily from Scopus, Web of Science, and ScienceDirect databases. Publications from approximately 2010 to 2024 were considered using keywords such as "nanocellulose isolation", "mechanical fibrillation", "acid hydrolysis yield", and "industrial scale-up of nanocellulose". Only English-language research and review articles were included. Particular attention was given to studies reporting quantitative indicators such as yield, energy demand, process scalability, and environmental implications.

3. Cellulose

Cellulose is a good and safe substance that is known to be the most durable polymer on earth that we can easily find. This material is systemic as microfibrils joined together to form fibrils of cellulose.

This is biosynthesized by living organisms such as algae, marine mammals, bacteria, and amoebae, producing this annually between 1010 and 1011 tons, although only a small portion of it is estimated to be 6 x 10^9 in manufacturing fields such as textiles, paper, and material industries[11]. Cellulose has traditionally been used as the most sustainable, organic raw material to support humanity for numerous local and industrial applications. Cellulose and its derivatives have found numerous uses for fiber, optical films, coatings, paper, food, pharmaceuticals, and cosmetics over the past 150 years[12].

In reality, Cellulose is still particularly important for researchers in a variety of fields due to its low cost, durability, resilience, and individual properties like high strength, biodegradability, and biocompatibility.

In several recent studies, the environmental implications have been a major factor in broadening the use of a multitude of simple and advanced products of cellulose and harnessing its essential properties[13].

3. 1- Structure and properties of cellulose

Cellulose is formed by a linear homopolysaccharide consisting of D-glucopyranose units combined by-β-1-4-linkages. Each monomer carries three hydroxyl groups and these hydroxyl groups and their ability to make hydrogen bonds play a central role in the management of crystalline packaging and also in the regulation of the physical properties of cellulose, So we may assume that cellulose micro fibrils are the key constitutional unit of cellulose produced during biosynthesis, poly chains-β- (14) -D-glucosyl residues combined to shape a fibril that is a long thread like a group of molecules laterally stabilized by molecular hydrogen bonds, shown inthe (Figure 1)[14]. The hydrogen bonds and the length of the molecular chains inhibit cellulose dissolution and help the quest for solvents to use cellulose effectively on a larger scale, given scaled-up processing challenges, remarkable progress has been made in the fields of energy, biomedicine, printed electronics, and infrastructure applications[15, 16].

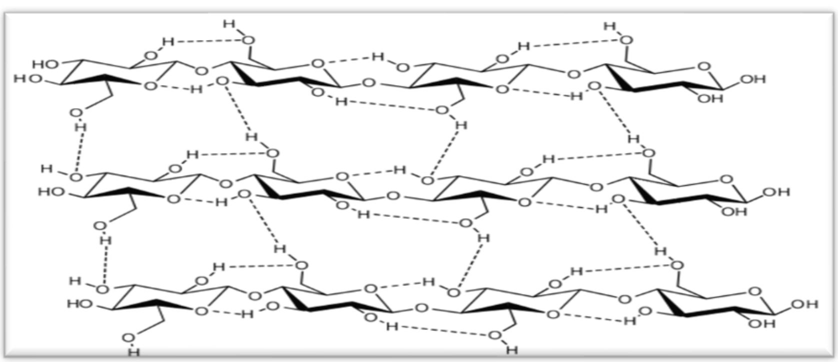

Figure 1: The molecular hydrogen bonds in the cellulose structure[16].

4. Nanocellulose

Nanoparticles are classified as particles with at least one dimension between [1-100] nm; the properties of materials at this scale vary from their symmetric material due to their high surface area to bulk ratio, so that novel products can be produced by selective manipulation. For thousands of years, forests have provided essential sources of lignocellulosic material resources that can be used for different applications.

Nanocellulose is widely used to classify different nanomaterials dependent on cellulose, such as Nanocellulose fibers, crystalline Nanocellulose, cellulose composites, etc. Table 1 shows that there are three main Nanocellulose subdivisions centered on features, shapes, manufacturing methods, sources, and reaction conditions:

- Bacterial Nanocellulose (BNC).
- Nanofibrillated cellulose (NFC).
- Cellulose Nanocrystals (CNC) [17].

Table 1: main types of Nanocellulose.

Type	Diameter (nm)	Length	L/D	Crystallinity (%)	Ref.
CNF (Cellulose Nano Fiber)	10-100	> 1 µm	70-100	84.9	[18, 19]
CNC (CelluloseNano Crystals)	4-25	100–500 nm	15-50	91.2	[20, 21]
BNC (Bacterial Nano Cellulose)	20-100	> 1 µm	50-100	70–80	[22,23]

The Active hydroxyl group found on the surface of Nanocellulose contributes to self-association. This property makes Nanocellulose a great supporter of composite matrix material for percolating load-bearing structures within a host polymer matrix [24, 25].

Cellulose fiber consists of piles of single cellulose fibers (25–30) µm in diameter. A single Cellulose fiber consists of microfiber bundles with diameters of (0.1–1) µm. The key microfibers are nanofibers, nanofibers which have a diameter of about (10–70) nm, and thousands of Nanometers in length [26].

The cellulose microfiber was shown as a fiber comprising continuous cellulose chains with a minimal hemicellulose and lignin content and a diameter of (0.1–1) µm with a total length of (2–20) µm. We can thus assume that cellulose nanofiber is a strictly crystalline cellulose chain with diameters in the range of (5-40) nm with a few microns in length [27].

Nanocellulose naming has not been used in a full uniform way in the past; some have employed the terms (MFC, BNC, and CNC), while others have used the term for bacterial Nanocellulose. The name microfibrillated cellulose (MFC is widely used in the scientific disciplines (Table 2)[16, 28].

Table 2: The classification of nanocellulose material [26].

Type of NC	Synonyms	Source	Processing method and characteristic
MFC	Microfibrillated cellulose, Nanofibrils, Microfibrils, Nanofibrillated cellulose.	Wood, sugar beet, potato tuber, hemp, flax, areca	Mechanical/ chemical/ enzymatic. Dia: 5-60 nm, length: several µms
CNC	Cellulose Nano Crystals, Crystallites, Whiskers, rod-like cellulose microcrystals	Wood, cotton, hemp, flax, wheat, straw, ramin	Acid hydrolysis. Dia: 5-70 nm , length : 100- 250 nm (from plant cellulose)
BNC	Bacterial cellulose , Microbial cellulose, biocellulose		Bacterial synthesis, diameter 20-100nm, different types of nanfiber networks.

Figure 2 shows sources of cellulose from plants, algae, and bacteria. Cellulose contains various parts, especially a crystal (very tidy) zone accompanied by some amorphous (untidy) small portions; separating the crystal regions from biomass led to the formation of polysaccharide NCs [29].

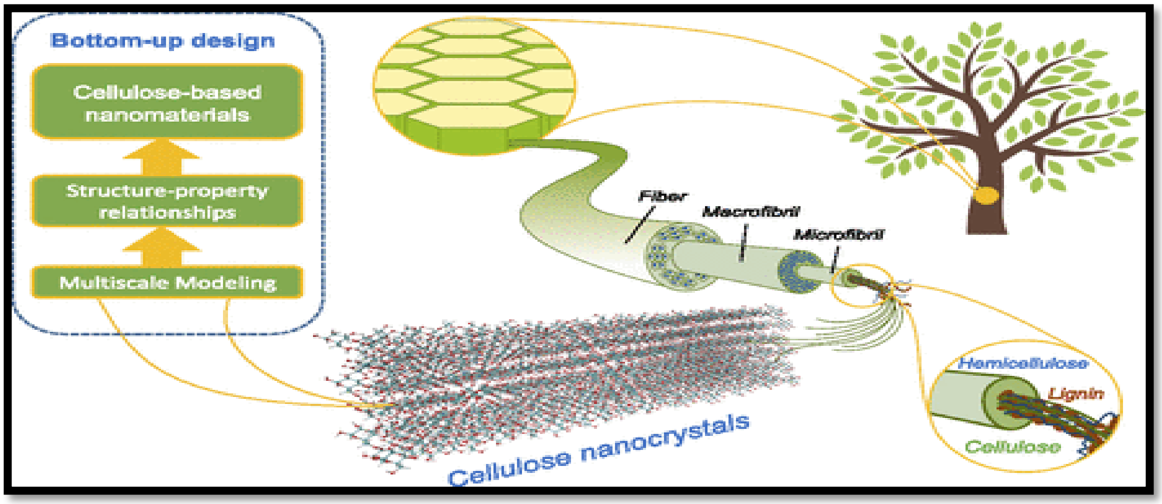

Figure 2: Schematic description of the lignocellulose biomass hierarchical structure down to nanocrystals of cellulose. (Left) The diagram shows how the atomic model of nanocrystals in cellulose is the starting point of the bottom-up design of nanomaterials based on cellulose[30].

So the attributes of nanocellulose are:

1. Light in weight
2. Nanocellulose itself is not electrically conductive but can be incorporated into conductive composites when combined with conductive materials.
3. Non-toxic
4. The crystalline structure is visible, and the gas is impermeable.
5. It can be generated cost-effectively in large quantities.
6. The tensile strength is very strong, 8 times that of concrete.
7. When utilized as a base for foams, it is incredibly absorbent.
8. The new material, cellulose, is the world's most available polymer **[31].**

4-1. Applications of Nanocellulose

The applications of Nanocellulose can be shown in a simple and detailed way through Table 4, where the applications were separated according to their common use since the start of knowledge of Nanocellulose and the conclusion of modern applications today.

Table 3: Applications of Nanocellulose[32].

Common applications	**Less common applications**	**New and emerging technology applications**
Cementum	Paint – OEM applications	Health, environmental, and industrial sensors
Automotive servicing	Paint – architectural	Water filtration system
Automotive interior	Paint – special purpose	Viscosity modifiers

Common applications	Less common applications	New and emerging technology applications
Packaging coatings	for the oil & gas derivatives industry	Reinforcement fiber construction
Wood and paper coatings	Aerospace structure	Air filtration system
Paper filler	Aerospace interiors	Cosmetics
Packaging filler	Insulation	Organic LED
Replacement–plastic packaging	Wallboard faces	Refinement
Plastic film replacement		Excipients
Textiles for clothing		Photonic films
Hygiene and absorbent products		3D printing for the office
		Recyclable electronics
		Photovoltaic
		Flexible electronics

We can say that because of its sustainable and biodegradable nature, and its unique characteristics, Nanocellulose has many potential applications that cover all important points, such as packaging, cement, paper, automotive, and niche items such as flexible electronics, sensors, and many more(Figure 3) [32].

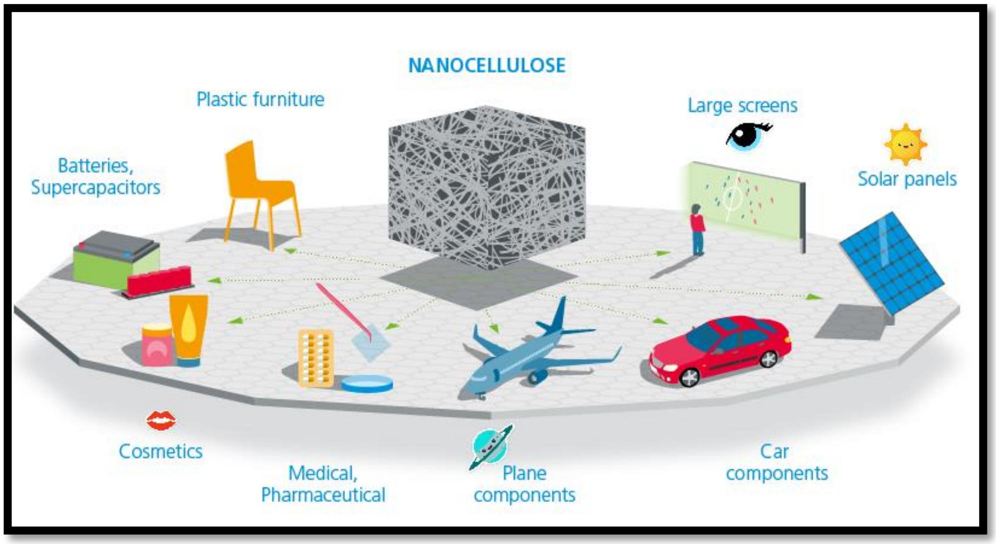

Figure 3: Important applications of nanocellulose [33].

In medicine, the special properties of Nanocellulose, especially bacterial Nanocellulose, make it really important in the development of medicine in the world. The scientists have demonstrated that bacterial cellulose is not toxic, due to excellent mechanical strength, permeability for liquids, gases, substances, and less inflammation of the wet-state Bacterial, so this material is widely used in medicine.

Bacterial Cellulose, which is often used as a dressing material in medicine because of its properties such as porosity, biocompatibility, sterility, and flexibility, often reduces pain, protects the skin against various infections, and does not cause loss of body fluid (Figure 4) [34].

In drugs, bacterial cellulose membranes have high potential for diffusion, promoting the transportation and absorption of drugs, giving them an advantage as an efficacious drug delivery, and retaining the ability to prevent loss. For example, when charged with Lidocaine and ibuprofen, BC membranes delivered positive outcomes with increased bioavailability and easy application [35]. Bacterial Cellulose drugs are used in the care of animals' wounds, dental implants, and also utilized in second and third-grade burns. The powdered nanocellulose is used in pharmacies as a very important *material.* It is used in the beauty industry in the manufacture of nanocellulose clothing, eyelashes, eyebrows, and nail dyes.

In addition, the high degree of hydration of BNCs (bacterial nanocellulose) is 99 %, so they can be used in the manufacture of moisturizing creams. It is also possible to use BNCs in the manufacturing of nano-implants, bandages, tissues, hydrogel, and certain other materials [36].

Figure 4: Applications of Nano Cellulose in medicine and drugs [37].

Nanocellulose can also be used in the active dissolution of cellulose in various solvents and in the manufacture of tobacco filters. In comparison, *compared* to quartz, cellulose nanocrystals *have* piezoelectric properties and also have photonic properties. Nanocellulose can *also* be found in the use of batteries, supercapacitors, *Bioplastics*, sensors, and in the use of composite structural materials, films, or coatings [37].

4-2. Conductive materials derived from nanocellulose

Conductive materials include metal atoms, carbon materials, and leading polymers. Primarily, these conductive materials can be combined with nanocellulose to create conductive compounds with high mechanical strength, rigidity, foldability, and durability. The development of a conductive composite based on Nanocellulose was primarily accomplished by grafting and combining conductive species with Nanocellulose [38, 39].

4-3- Luminescent devices - based on nanocellulose

In recent years, alternative approaches for making the devices of light-emitting devices have been explored in polymers and nanoparticles with various chemical structures emitting colors across the entire visible area.

New improvements in bio-based sensing, organic solar cells, and organic field transistors are designed to take place rapidly in order to switch from conventional to inexpensive and versatile conductive. These applications are: luminogens and fluorescently based on nanocellulose [40, 41].

***5. Nanocellulose* and the Food Industry**

Instead of several starch goods presently in use, Nanocellulose can be used in the manufacture of foods such as pastes, sauces, wafers, pudding, candy, etc., as low-calorie goods. Nanocellulose gels have been widely used in this field in recent years due to their rheological properties **[42]**.

6. Industrial Scale-Up Challenges and Economic Limitations

While the facts surrounding nanocellulose are undeniably compelling under managed lab conditions, the fact will become all the more tangled the instant we strive to shift those outcomes to the manufacturing unit floor. In undeniable phrases, scaling up production is not often a linear equation in which you simply multiply the inputs. Once you transition to a continuous production gadget, reactors start to behave in ways we do not see in small-scale glassware, frequently introducing fluctuations in parameters that have been previously stable.

Take mechanical traumatic inflammation, for example. It is regularly marketed as the "green" opportunity, but the sheer electricity demand at a business scale remains a harsh monetary reality. While pre-treatment strategies can take a number of the load off, their performance is often at the mercy of uncooked material variability—moisture ranges and biomass great range, as does the system itself. This is exactly why we see such inconsistent power information throughout different studies and companies; the consequences certainly aren't without delay comparable in a actual-international placing.

Then there's acid hydrolysis—a conventional case of the distance between "viable" and "realistic." Yes, it gives specific management over crystal morphology, but the hidden costs of constructing a plant capable of acid recovery, the usage of corrosion-resistant alloys, and dealing with wastewater treatment add layers of capital expenditure that might hardly ever be the focal point of pilot studies. From a simple engineering point of view, those "peripheral" costs can absolutely constitute the lion's share of the investment.

Beyond the hardware, we are facing the hurdle of batch-to-batch consistency. A mild shift in temperature or shear force in a big reactor can right now warp the particle length distribution, threatening the reliability of the very last product in sensitive programs. Ultimately, the real task isn't simply proving that the fabric works in a lab; it's about harmonizing that innovation with stable processing, affordable electricity footprints, and bloodless, hard economic constraints. How properly we bridge those gaps will, in the end, dictate how fast the enterprise clearly adopts this generation.

7. Conclusion

Research on cellulose and nanocellulose has progressed significantly, and the range of demonstrated applications continues to expand. Advances in morphology control, surface functionalization, and composite integration have strengthened confidence in their technical potential across biomedical, packaging, and energy-related fields.

Nevertheless, the pathway toward industrial maturity remains uneven. Energy consumption, production cost, and process standardization continue to influence adoption decisions more strongly than laboratory performance alone. In this context, interdisciplinary collaboration between materials scientists and process engineers becomes particularly important.

While research on nanocellulose has undoubtedly expanded in scope and technical sophistication, industrial maturity depends less on demonstrating additional functionality and more on achieving energy efficiency, cost balance, and process reproducibility. Addressing these practical dimensions may ultimately determine whether nanocellulose evolves from a promising research material into a stable industrial platform. Continued collaboration between academia and industry will likely play a decisive role in narrowing the gap between laboratory innovation and commercial implementation.

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9.1 Ethics approval and consent to participate:

This study does not involve human participants or animals. Therefore, ethical approval and consent to participate were not required.

9.2 Consent for publication:

Not applicable.

9.3 Availability of Data and Materials:

The data supporting the findings of this study are available within the article. Additional data may be obtained from the corresponding author upon reasonable request.

9.4 Conflicts of interest:

The authors declare that they have no competing interests.

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أهمية السليلوز والنانوسليلوز، وبنيتهما، وخصائصهما، وتطبيقاتهما .مراجعة

رشا شاكر محمود [1]، يونس تركي محمود [2]

الجامعة المستنصرية، كلية العلوم، قسم الكيمياء، بغداد، العراق [1]
جامعة الموصل، كلية التربية للعلوم الصرفة، قسم الكيمياء، الموصل، العراق [2]

ملخص:

اكتسبت ألياف السليلوز أهمية بالغة في حياتنا خلال السنوات القليلة الماضية، فهي المكون الرئيسي للألياف النباتية، وتتميز بخفة وزنها ومتانتها، فضلاً عن كونها غير سامة وصديقة للإنسان والبيئة. تُعدّ مجموعات الهيدروكسيل من أهم المجموعات الفعالة في تركيب السليلوز، إذ يفتح وجودها آفاقًا واسعة لاستخداماته من خلال التفاعلات الكيميائية التي تحدث عبر هذه المجموعات عند توفر الظروف المناسبة. لذا، سنقدم أولًا شرحًا مبسطًا عن السليلوز، وبنيته، وخصائصه النموذجية؛ ثم ننتقل إلى شرح مبسط عن النانوسليلوز، وخصائصه، ومميزاته الفريدة، ومصادره الرئيسية، وابتكاراته، وتطبيقاته المتقدمة.تشرح المقالة التركيب الكيميائي للسليلوز، والذي يتكون من وحدات جلوكوز مرتبطة بروابط، وتحتوي على مجموعات هيدروكسيل فعالة تلعب دورًا رئيسيًا في تحديد خصائصه الفيزيائية والكيميائية، مثل القوة العالية والقدرة على تكوين روابط هيدروجينية.كما تركز الدراسة على النانوسليلوز، وهو الشكل النانوي من السليلوز، والذي يتميز بمساحة سطحية عالية وخصائص ميكانيكية متفوقة. ويتم تصنيفه إلى ثلاثة أنواع رئيسية:السليلوز النانوي الليفي 1- (CNF).